A CRITICAL EVALUATION OF THE OPERATION AND PERFORMANCE OF LAGOONS IN COLD CLIMATES

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Contract 14SU.KE145-2-0675

October 31, 1983

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ABSTRACT

This review was initiated in an effort to identify and compile the existing body of information regarding cold climate sewage lagoons. Past performance, process theory, process design, facility design and construction, and operation were critically reviewed with the intent of identifying the current state-of-the-art of cold climate lagoons. Research and development needs in each topic area were identified for future reference.

Over 400 titles were referenced in the course of preparing this report. Special sub-sections were devoted to geotechnical considerations, upgrading alternatives, and the impact of lagoon effluent on the environment and public health. Permafrost engineering of lagoon berms and foundations were discussed and past experiences reviewed. Lagoon upgrading options for cold climates were evaluated as were the economics of lagoons for small communities.

Twenty-three research and development topics were identified in the course of the review. These may be addressed by a combination of literature reviews, laboratory studies, and field investigations.

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1. INTRODUCTION

1.1 SCOPE

Lagoons are the most frequently used wastewater treatment process in Canada. The main reason for such popularity are low capital and operating costs. During periods of relatively warm weather and adequate sunlight, the treatment performance in terms of biochemical oxygen demand (BOD) and fecal coliform (FC) reduction is good. In periods of cold weather and limited sunlight, the treatment performance is poor. The variability of lagoon treatment performance has caused a considerable amount of concern among designers, operators, and regulating agency staff. A number of design and operational modifications have been developed to overcome such limitations of the process.

This report has been limited to a critical review of information on the design, operation, and performance of sewage lagoons in the northern part of Canada. In particular, information in the report has been limited to regions where lagoons form seasonal ice cover. As a result information from the northern United States, Canada, and Alaska has been included.

1.2 OBJECTIVES

This report has four objectives:

1. compilation of literature and data on lagoons in cold regions;
2. review of literature and data;
3. evaluation of present and past design and operation approaches; and
4. identification of topics where insufficient information exists for optimal design and operation.

The report has been organized on the basis of process, operational, geotechnical, and environmental considerations.

1.3 TERMINOLOGY

The terminology which has developed for identifying lagoon types varies widely and can be confusing with many authors developing terms to suit the needs of the moment.[1,2,3] In this report four basic types of lagoons will be recognized:[1,4]

1. aerobic;
2. facultative;
3. anaerobic; and
4. mechanically aerated lagoons.

Many hybrid lagoon configurations have evolved from these basic groups.

The term lagoon has been widely abused,[1] being generally defined as a shallow body of water contained in an earthen basin, which is designed for the treatment of wastewater.[4] The terms, waste stabilization pond, sewage pond, oxidation pond, sewage lagoon, stabilization pond, and waste pond have all been used to describe the same basic process.[2]

In this report, the term lagoon will be defined as a designed, shallow earthen basin for the primary and secondary treatment of wastewater. It is operated hydraulically using a submerged outlet and frequently with a submerged inlet. A pond consists of a depression operated hydraulically with an outlet from the surface as in the case of lakes.

1.4 HISTORICAL DEVELOPMENT OF LAGOONS

Allum[2] conjectured that waste stabilization ponds were invented by the Chinese 1000 years ago. The use of lagoons in North America date back to 1901, when San Antonio, Texas constructed a wastewater impoundment.[1]

Since that time, many lagoons have been constructed and operated, some successfully and others not, usually due to the fact that engineering of the process was non-existent until the mid 1950's.[1]

One of the first sewage lagoons built in Arctic North America was at Ft. Yukon, Alaska in 1957,[4] followed by more at U.S. Air Force bases in the 1960's.

Western Canadian experience was initiated during the late 1940's and early 1950's by Alberta, Saskatchewan, and Manitoba, which built more than 400 lagoons by 1961.[7] The first Canadian Arctic lagoon was constructed at Inuvik in 1957[8] though Yellowknife was using Niven Lake to receive wastewater in 1949.[7] [9] Ontario first installed lagoons in 1956 at the Ipperwash Army Camp and their number grew to 43 by 1964.[10] The Maritime experience is contemporary with that of Ontario, the first lagoon being installed in 1957 at O'Leary, Prince Edward Island.[10]

Historically, water demand has been closely linked to population and the type of water distribution system.[11] [12] [13] This directly influences the type of waste disposal system required. Typically in the north, homes have water hauled by truck to them on a regular basis. However, several communities have piped water.[14] Waste collection is either by honey bags, storage tanks, (with truck hauling) or conventional sewerage.[13] [14] The first two methods produce concentrated and moderately dilute wastes, respectively, while piped water supply produces conventional wastewaters. A problem, unique to the north, is highly diluted wastewater, the result of bleeding water distribution systems into the sewers for freeze protection.[13] [15]

Heinke and Prasad[16] studied the problem of concentrated human waste and considered lagoons to be inappropriate for

disposal of these wastes. Smith and Christensen[3] reported the use of lagoons for all other classes of wastewater in the north.

The policy of the Northwest Territories Government has been towards using piped water distribution systems which will produce a conventional wastewater.[3]

The problem of cold climate biological treatment of conventional wastewater has been studied in some detail providing a basis for the design and operation of treatment facilities.[4] [9] [11] [12] Even though the level of biological activity is greatly reduced during the winter months, the conclusion has been repeatedly drawn that the use of wastewater treatment lagoons is the best treatment alternative for the following reasons:[4] [13] [23]

1. reduced capital costs;
2. low maintenance levels;
3. minimal energy requirements;
4. skilled operators are not required;
5. availability of inexpensive land; and
6. small populations are adequately served.

1.5 INVENTORY OF CANADIAN LAGOONS

As of 1981, according to the National Inventory of Municipal Waterworks and Wastewater Systems in Canada,[24] there were 746 lagoon systems operating in Canada. A geographical distribution of lagoon use is summarized in Table 1.1. Approximately half of the wastewater treatment systems reported in Canada are sewage lagoons. Alberta, Manitoba, the Northwest Territories, Saskatchewan, and the Yukon Territory rely heavily on lagoons for wastewater processing.

It is not a coincidence that these regions are also the most sparsely populated in Canada since it is generally acknowledged that lagoons are the most cost effective form of waste treatment for small communities.[1,4,8,11,13,21]

A detailed inventory of water and wastewater treatment facilities in Canada is available from the Minister for Supply and Services through Information Canada.[24] This source provided a provincial and territorial summary, including a breakdown on a community basis, of total population, population with municipal services, type of treatment facility, average flowrates, level of treatment, disinfection, and other relevant information.

For information dealing specifically with the Yukon and Northwest Territories, Smith and Christensen[13] provided a good summary.

Table 1.1 - Lagoon Use in Canada[24 25]

Location	Number of Lagoons	As a % of Treatment Facilities
Alberta	278	84
British Columbia	34	31
Manitoba	127	85
New Brunswick	58	63
Newfoundland	1	2
Northwest Territories	15	71
Nova Scotia	14	16
Ontario	128	33
Prince Edward Island	17	9
Quebec	59	21
Saskatchewan	129	92
Yukon Territory	8	70
Canada	868	48

1.6 PERFORMANCE RECORD

There is a wealth of performance data in the literature and even more which is unpublished. For example, there is a companion document[24] to the Canadian inventory[24] of wastewater treatment facilities, which listed performance data for the municipalities in the published inventory. The completeness of the data varied. However, important parameters such as BOD removal, operating mode, number of cells, and effluent disposal method were included.

The literature contained many reports on lagoon performance.[27 28 29 30 31 32 33 34 35 36 37 38 39 40 41] A major problem with reported data is that it presents time dependent, hence seasonal, parameters as discrete data points. Therefore, it is difficult to draw conclusions or establish mathematical performance relationships. The best which can be hoped for are ranges of variation for key performance parameters such as BOD, suspended solids, nutrients, and indicator microorganisms.

Table 1.2 is a performance summary of lagoons operated in the Northwest and Yukon Territories as of 1981.[8 24 26 35 43] Table 1.3 summarizes other relevant performance reports found in the literature. These tables illustrate that performance reporting is inconsistent for cold climate lagoons and that summer performance is comparable to that of southern, warm weather facilities. Dawson[43] provided a good summary of lagoon performance in the Northwest Territories as of 1967.

Table 1.2 - Summary of Present Lagoon Performance North of 60

Location	Latitude (approx.)	Population Total/Served	Collection System	Lagoon Type	No. Cells	Op. Mode	Discharge Mode	Retention Time (d)	Daily Org. Loading kg BOD	BOD Removal %	S.S. Removal %	Remarks
Baker Lake, NWT	64°18'N	1062/1062	tank/bad	fac.	2	series	cont.	1891				Natural lakes
Enterprise, NWT	60°15'N	40/40	tank	anaer.	1	--	cont.					Natural pond
Eskimo Pt., NWT	61°05'N	994/994	tank/bag	anaer.	1	--	cont.					Mod. pond
Ft. Franklin, NWT	65°11'N	545/545	tank/bag	anaer.	1	--	intermit.	180				Spring & fall discharge
Ft. McPherson, NWT	67°27'N	793/200	pipe/tank/bag	other	1	--	cont.					Natural lake
Ft. Norman, NWT	64°54'N	359.359	tank/bag	fac.	1	--	cont.					
Ft. Providence, NWT	61°21'N	554/554	tank	anaer/fac	4	par/ser	intermit	365				Spring discharge
Ft. Smith, NWT	6-°00'N	2297/2297	pipe	anaer/fac	3	par/ser	cont	90	24/ha	50-90	80-95	
Hay River, NWT	60°51'N	3129/3129	pipe	anaer	3	par/ser	cont.					
Inuvik, NWT	68°21'N	2929/2929	pipe	fac	1	--	cont		16/ha	70-90	85	
Pine Pt., NWT	60°50'N	1647/1647	pipe	anaer	2	series	cont					
Rae, NWT	62°50'N	1350/1350	bag	fac	1	—	none	long				Twin towns
Edzo, NWT	62°50'N		pipe	fac	2	par/ser	cont.	51				
Tuktoyaktuk, NWT	69°27'N	762/762	bag/tank	other	1	—	none	long				Natural lake
Yellowknife, NWT Niven Lake	62°28'N	9550/9140	pipe	fac.								Natural lake system
Faro, Y.T.		1800/1800	-	anaer/fac	-	-	-	-				
Haines Jct, Y.T.		450/350	-	anaer	-	-	-	-				
Teslin, Y.T.		300/150	-	anaer/fac	-	-	-	-				
Watson Lake, Y.T.		809/600		fac	2	series	intermit			50		Discharge bimonthly
Whitehorse, Y.T.	63°43'N	16929/15200										
Crestview		/200		anaer/fac	--	--	--	--	--	--	--	
Porter Creek		/5000		anaer	4	ser	cont	17	—	39	53	
Whitehore		/10000	pipe	anaer	4	par/ser	cont	20	0.01/m^3	41	60	

Table 1.3 - Summary of Past Performance of Typical Lagoons

Location	Latitude (approx.)	Population Total Served	Lagoon Type	No. Cells	Op. Mode	Discharge Mode	Retention Time (d)	Daily Org. Loading kg BOD	BOD Removal %	S.S. Removal %	Reference
Moose Jaw, Sask.	50°20'N	35,000	anaer. aerobic	2 2	par par	cont intermit	7 93	1212/ha 54/ha	40 85	65 65	Brisbin et al (28)
Hay River, N.W.T	60°51'N	1700	anaer	2	par/ser	cont.	5	0.03/m^3	43	81	Slupsky et al (34)
College, Alaska	65°00'N	1600	ox. ditch	--	--	cont.	--	--	90	--	Grube et al (39)
Fayette, Missouri	40°00'N	3144	fac.	6	par/ser	cont	88-150	20-100/ha	72-90	--	Neel et al (37)
Canora, Sask.	52°00'N	--	fac	1	--	--	--	12/ha	66-100	95-78	Prescott (38)
Wynyard, Sask.	52°00'N	--	fac	2	sec	--	--	--	85	37	ibid
Kamsack, Sask.	52°00'N	--	fac	1	--	--	--	13/ha	50-95	79-21	ibid
Dayeland, Alta.	52°00"N	350	anaer	1	00	cont.	6.0	3000/ha	50	--	Alberta Gov't. (33)
Stony Plain, Alta.	52°00'N	1040	anaer/fac	4	ser	cont	200	5000-10/ha	69-98	--	ibid
Calmar, Alta.	52°00'N	600	anaer/fac	2	ser	cont	65	100/ha	72	--	ibid
Holden, Alta.	52°00'N	450	fac	1	--	cont	275	22/ha	72-82	--	ibid
Lacombe, Alta.	52°00'N	2835	fac	1	--	cont	205	28/ha	38-82	--	ibid

The data is sparse and some sources[3,4] do not indicate if the reported numbers are yearly averages or instantaneous samples, an important difference for cold region lagoons. As illustrated in Tables 1.2 and 1.3 the organic loading is often difficult to determine since flow rates are rarely measured and lagoon geometry is not presented.

Another problem has been the use of percent reduction for BOD, SS, and coliform organisms. The general practice is a comparison of influent concentrations with effluent concentrations but in a multi-cell system it often is not clear if the final effluent or inter-cell values are reported. A distinction between filtered and unfiltered BOD_5 data is often not made which significantly affects the interpretation.[4] McKinney[44] discounted the use of influent:effluent ratios in algal based treatment systems since they were not related in that process.

In the case of coliform reduction, the use of $\log_{10}$ reduction is preferred but is rarely used, causing misleading use of the data. For example, 90 percent reduction of 10^7 organisms per 100 mL may have 10^6 organisms per 100 mL remaining. This impressive performance in reality is only one $\log_{10}$ unit reduction.[43]

There are no national effluent regulations which are binding, each province and territory being responsible for the standards in their jurisdiction. As an example, the Northwest Territories[44] has water quality guidelines based on the dilution

capacity of the receiving waters. Effluent BOD_5 ranges from 30 mg/L to 600 mg/L, for small streams to ocean outfalls, respectively. Similarily, allowable effluent suspended solids range from 35 mg/L to 725 mg/L. Total coliforms have permissible levels of from less than 10^3/100 mL to unlimited. Lagoons operated at temperatures from 15° to 20° C are able to meet the lower concentration value given proper design and operation.[47, 48]

Winter performance deteriorates since ice and snow cover, combined with near freezing water temperatures, reduce the action of the lagoon to that of a sedimentation basin.[49] Figure 1.1 illustrates this decline in performance for BOD_5, suspended solids, and fecal coliforms in typical cold region facultative lagoons. In recognition of this, many lagoons are designed for intermittent discharge and long retention times.[7, 20]

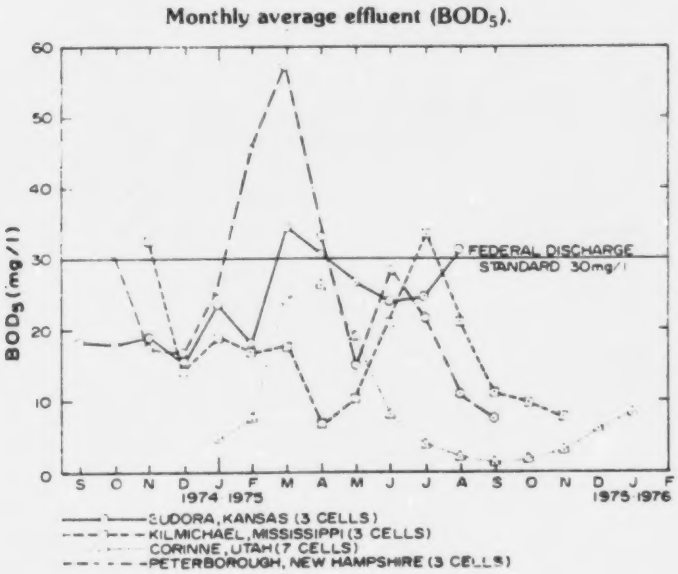
1.7 PROBLEMS

It is evident from the literature that some problems are common to many lagoon systems. They may be process or design related.[49] The most common problems cited included odours,[33] water loss,[50] insects,[51] safety,[52] erosion,[49] sludge accumulation,[53] and failure to meet effluent standards during the winter.[47]

A detailed discussion of the causes and control of these problems is presented in subsequent sections.

Figure 1.1 - Seasonal Performance Variation (from Middlebrooks *et al*[47])

(a) **BOD**


Monthly average effluent (BOD_5).
BOD_5 (mg/l)
FEDERAL DISCHARGE STANDARD 30mg/l
S O N D J F M A M J J A S O N D J F
1974 1975
1975 1976
EUDORA, KANSAS (3 CELLS)
KILMICHAEL, MISSISSIPPI (3 CELLS)
CORINNE, UTAH (7 CELLS)
PETERBOROUGH, NEW HAMPSHIRE (3 CELLS)

(b) **SUSPENDED SOLIDS**

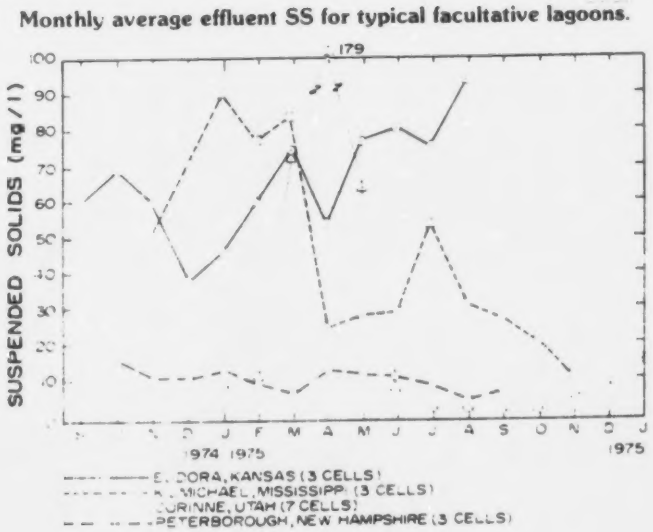
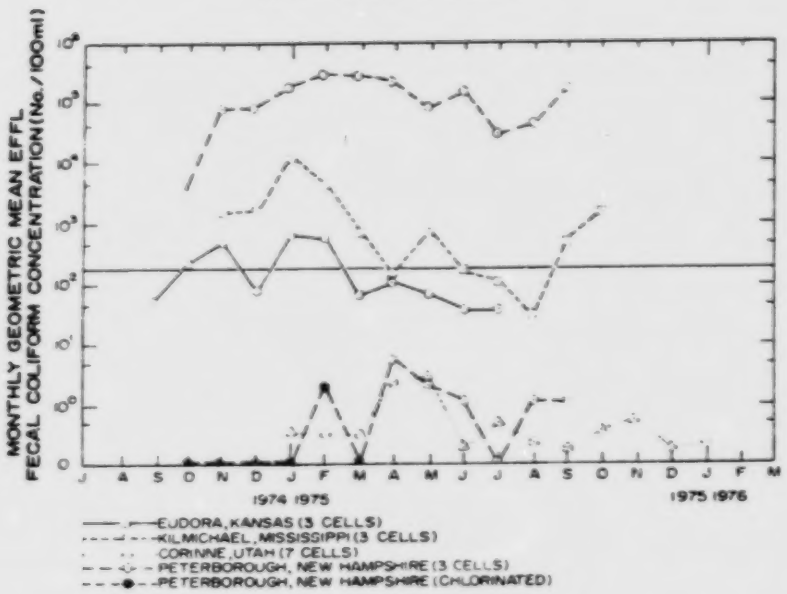


Figure 1.1 - continued

(c) **FECAL COLIFORMS**

Effluent monthly geometric mean fecal coliform concentrations from typical facultative lagoons.


MONTHLY GEOMETRIC MEAN EFFL FECAL COLIFORM CONCENTRATION (No./100ml)
0
J A S O N D J F M A M J J A S O N D J F M
1974 1975
1975 1976
EUDORA, KANSAS (3 CELLS)
KILMICHAEL, MISSISSIPPI (3 CELLS)
CORINNE, UTAH (7 CELLS)
PETERBOROUGH, NEW HAMPSHIRE (3 CELLS)
PETERBOROUGH, NEW HAMPSHIRE (CHLORINATED)

1.8 CRITIQUE

A review of performance data for lagoons in Alaska, Canada, and the northern United States, indicates that there are no uniform criteria for reporting lagoon performance. Lagoon effluent characteristics have little relationship to the influent raw wastewater making percent reduction performance reporting meaningless. Also, qualitative performance analysis is difficult to interpret in terms of meeting quantitative standards.

A second observation is that few comprehensive studies of existing cold climate lagoon systems have been carried out in North America. Of Canadian facilities, the lagoon at Inuvik has had the most long term attention.

Considering that over one half of the wastewater treatment facilities in Canada are lagoons, there is surprisingly little research carried out given the conflicting reports on performance, particularily during the winter months.

2. THEORY OF LAGOON TREATMENT

2.1 INTRODUCTION

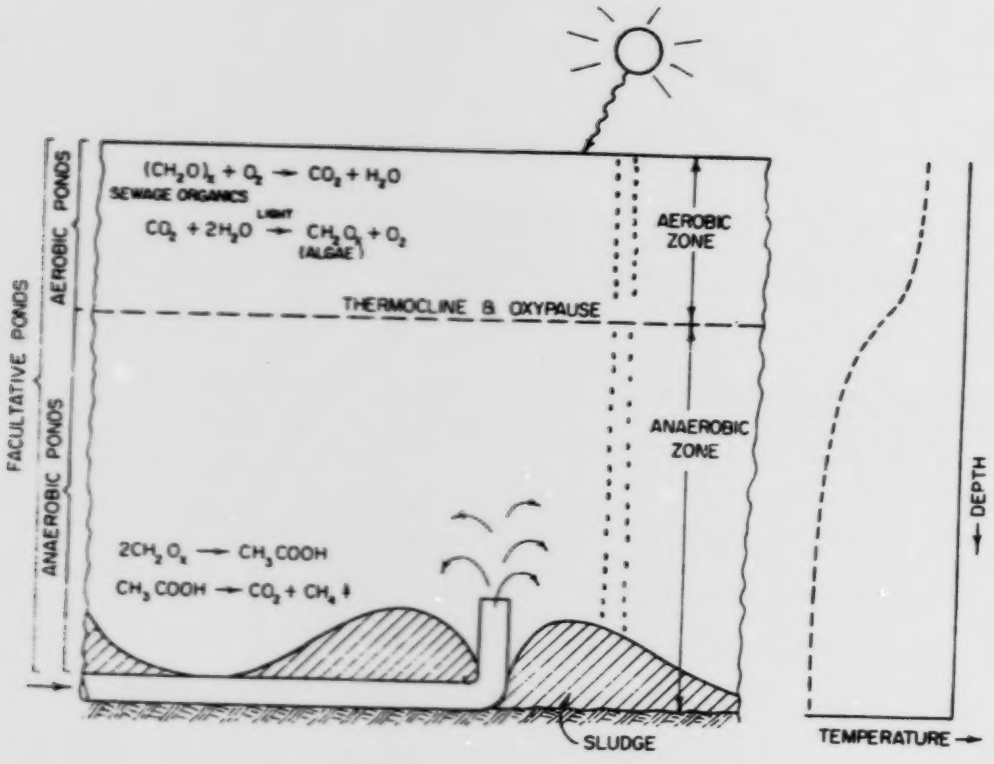
Facultative or long retention polishing lagoons have been used the most extensively in Canada. This type of lagoon is illustrated schematically in Figure 2.1 and consists of an aerobic surface zone containing photoautotrophic algae and aerobic bacteria. The bacteria generate carbon dioxide as a metabolic end product which the algae use as a carbon source and under conditions of adequate light the algae produce oxygen and new cells. The anaerobic benthic zone contains obligate anaerobes which digest the deposited organic solids and cell material. The transition zone finds a population of facultative anaerobes metabolizing suspended organic matter.

2.2 BIOLOGICAL PROCESSES

2.2.1 Microbiology

A lagoon system contains two main types of microbial cells which are responsible for the stabilization of wastes. These are the eucaryotes and the procaryotes, the former having a true nucleus which the latter lacks. Bacteria and cyanobacteria (formerly blue-green algae) are procaryotes and algae, fungi, and protozoa are eucaryotes.[54] A few researchers have attempted to determine the ecology of a sewage lagoon.[53, 54]

Figure 2.1 - A Schematic of a Facultative Lagoon (from Oswald[17])



2.2.1.1 Bacteria

Metcalf and Eddy[4] noted that the aerobic bacteria found in a facultative lagoon were similar to those of an activated sludge whereas anaerobic bacteria were the same as those found in anaerobic digestion. Cyanobacteria are aerobes found in lagoons but not in an activated sludge.

Activated sludge is characterized by heterotrophic, gram-negative bacteria with lesser numbers of autotrophic organisms. The former include species of the genera *Pseudomonas*, *Zoogiea*, *Achromobacter*, *Flavobacterium*, *Nocardia*, *Bdellovibrio*, and *Mycobacterium*. The autotrophic group include members of the genera *Nitrosomonas* and *Nitrobacter*.[4, 53] Of the facultative anaerobes, *Pseudomonas spp.*, *Vibrio*, *Aeromonas*, and *Chromobacterium* are the most common.

Since a lagoon environment is much less controlled than the activated sludge process, lagoons have microbial populations which change in response to environmental changes. Seasonal variation in temperature and competition for food largely determine the dominant group.[53] For example, pseudomonads dominate biological waste treatment processes because of their ability to utilize a wide range of organic substrates.[54]

Temperature effects on bacterial populations in activated sludge waste treatment was studied by Henry.[53] He found that genera associated with mesophilic temperatures had species which were psychrophilic. He reported that temperature changes were

significant in population dynamics causing a shift towards psychrophiles at low temperatures. No single genus dominated. Miller[10] reviewed the biochemical bases of psychrophiles and concluded that true psychrophiles have growth rates at low temperatures comparable to those of mesophiles at higher temperatures. Therefore, the kinetics of biochemical reactions were not necessarily slower at cold temperatures. Roberts *et al*[11] reported the state of knowledge on psychrophilic metabolism. Differences in cell wall permeability were thought to account for the efficient utilization of glucose by psychrophiles at low temperatures. Psychrophiles have been reported in cold region lagoons.[12] [13] Boyd and Boyd[14] found the number of psychrophiles represented a small proportion of the population, probably due to competition from psychrotrophic mesophiles originating in the sewage.

Cyanobacteria have been found in lagoons in large numbers on occasion. They are non-motile, photoautotrophs and are unable to grow in the dark or on an organic substrate.[15] The genera *Oscillatoria* and *Anabaena* are typical.[16]

The anaerobic sludge zone contains two main groups of obligate anaerobic organisms; the so-called acid formers and the methane generators. The former group includes members of the genera *Clostridium*, *Peptococcus*, *Actinomycetes*, *Bifidobacterium* and *Corynebacterium*. Methanogenic organisms include *Methanobacterium*, *Methanococcus*, *Methanospirillum*, and *Methanosarcina*.[4] [17] These bacteria are usually of mesophilic or

thermophilic nature. Schneiter *et al*[11] speculated that facultative, psychrophilic bacteria were involved in reducing sludge volumes in Alaskan aerated lagoons.

Other groups are involved in the reduction and oxidation of sulphur. These anaerobes include *Desulfovibrio* which is the most common sulphate reducer and *Thiopedia*, *Thiocapsa*, and *Chromatium* the purple and green (sulphur) bacteria which oxidize sulphide.[11]

2.2.1.2 Algae

The genera found in sewage lagoons have been documented by Hilliard,[8] Goulden,[9] and others.[7] [10] [12] Gloyna[1] found *Chlorella*, *Scenedesmus*, *Chlamydomonas*, and *Euglena* to be the most common green algae and *Nitzchia* to be representative of green-brown algae or diatoms. He also reported that *Euglena* and *Chlamydomonas* were the hardiest algae, being first to recover from anoxic events and being insensitive to cold water. This was supported by other authors.[8] [13] Reports by Patrick[14] and others[13] [15] of viable psychrotrophic algae under ice cover confirms that given sufficient light, aerobic conditions can be maintained during the winter.

The genera which dominate at any given time is a function of temperature, light intensity, and mixing.[4] Uhlmann[17] studied phytoplankton (algae) production in hypereutrophic waters such as sewage lagoons. Under conditions of optimum nutrients, temperature, detention time, and light the algal mass never achieved predicted concentrations. This was attributed to

predacious zooplankton (crustaceans, rotifers). Polprasert *et al*[40] noted algal concentration was a function of algae species, pH, and dissolved oxygen. McKinney[44] observed that even non-motile algae are able to move into zones of optimum lighting. He also remarked on the phenomenon of algae die-off during rapid changes in temperature in the autumn. He speculated that it is caused by supercooling and freezing of the algal protoplasm.

2.2.1.3 Protozoa and Higher Animals

McKinney[39] provided a concise account of the role of protozoa, crustaceans, and rotifers in lagoons. The most important group was Ciliata, the ciliated protozoa which are highly motile and adapted to the efficient capture of bacteria. Typical genera include *Paramecium*, *Glaucoma*, *Euplotes*, and *Colpidium*. The stalked ciliate, *Vorticella*, has also been observed.

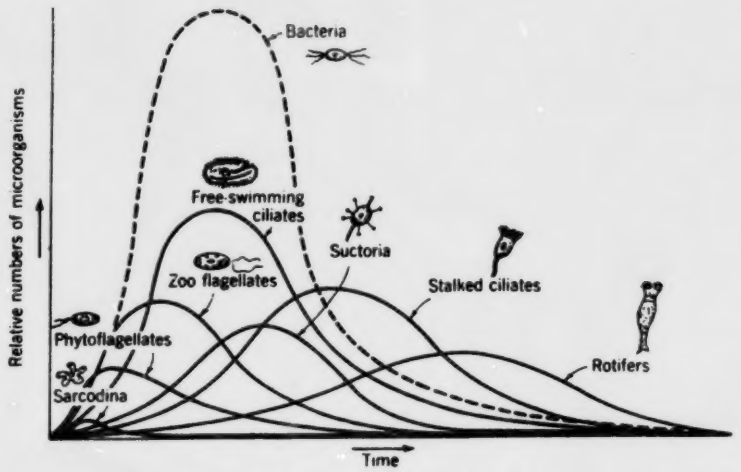
Crustaceans survive on bacteria and algae. They filter large quantities of water in their quest for sufficient nutrients. Typical genera include *Cyclops*, *Diaptomus*, *Daphnia* and *Moina*.[39] [41] [43] *Daphnia* was reported to be the most important crustacean by several authors.[39] [41] [43] [43] [44]

Rotifers are the scavengers of the lagoon, cleaning up large organic particles, algae, bacteria, and cellular debris.[1] [39] Ahmed[43] found fungi to be active in removing organic matter from oxidation ponds located in India.

2.2.1.4 Population Dynamics

Population dynamics are very important in determining the efficiency of a biological process. Maximum efficiency occurs when a proper mix of microorganisms is present. Figure 2.2 shows a typical mix for an activated sludge. Metcalf and Eddy[4] noted this was similar to the aerobic region of a facultative lagoon.

Figure 2.2 - Typical Population Mix of Activated Sludge (from McKinney'[9])



Relative growth of microorganisms in stabilization of liquid organic wastes. (*Note:* Numbers of microorganisms are not to same scale, but are expanded for clarity.)

2.2.2 Biochemistry

This topic deals with the chemistry of converting waste using biological processes.

Simply considered, microbial cells contain about 50% carbon, 20% oxygen, 10-15% nitrogen, 8-10% hydrogen, 1-3% phosphorus, and 0.5-1.5% sulphur on a dry weight basis.[5] Many trace metals are also present. A commonly used chemical expression for cell material is $C_5H_7O_2N$.[44] McKinney[44] used $C_5H_9O_{2.5}N$.

Detailed molecular composition is beyond the scope of this review, however it will suffice to mention that the cells are composed of nucleic acids, carbohydrates, proteins, and lipids.[44]

An historical review of the biochemical reactions in a lagoon was provided by Vennes.[44] Ganapati[37] reviewed biochemical reactions in high-rate ponds.

Aerobic stabilization of organics in a lagoon system hinges upon two simplified equations;

(1) $5CO_2 + 3H_2O + NH_3 \rightarrow C_5H_9O_{2.5}N + 5.25O_2$

(2) $6(CH_2O)_x + 5O_2 \rightarrow (CH_2O)_x + 5CO_2 + 5H_2O$

Equation (1) was proposed by McKinney[44] and describes algal activity. Abeliovich and Weisman[44] found that *Scenedesmus obliquus* derived 15 percent of its carbon requirements from glucose, an organic carbon compound. Equation (2) is after Oswald[37] and represents the aerobic metabolism of heterotrophic

bacteria.

Anaerobic biochemical conversions in the benthic zone concern the reduction of organic compounds to organic acids (Equation 3) and subsequent methanogenesis (Equation 4). Also of particular interest in lagoons is the reduction of sulphates (Equation 5) and the oxidation of sulphides (Equation 6), the usual causes of odours.[3]

(3) $5(CH_2O)_x \rightarrow (CH_2O)_x + 2CH_3COOH$

(4) $2.5CH_3COOH \rightarrow (CH_2O)_x + 2CH_4 + 2CO_2$

(5) $1.5CH_3COOH + SO_4^{2-} \rightarrow (CH_2O)_x + 2H_2S + 2CO_2 + 2OH^-$

(6) $(CH_2O)_x + CO_2 + H_2S \rightarrow 2(CH_2O)_x + H_2 + 2S$

An obligate aerobe, *Thiobacillus* is capable of oxidizing sulphides. Its presence relies on adequate oxygen and sulphide concentrations but since molecular oxygen quickly oxidizes sulphide, conditions are rarely present to encourage its growth in a lagoon.[3]

2.2.3 Nutrient Removal

It is known that cyanobacteria utilize nitrates or ammonia as a nitrogen source. Some genera fix nitrogen.[4]

The nitrification-denitrification processes occur in the lagoon environs and are defined by the following biochemical reactions.[3] Equations (7) and (8) require aerobic conditions whereas equation (9) is carried out by facultative bacteria.

(7) $2NH_3 + 3O_2 \rightarrow 2NO_2^- + 2H^+ + 2H_2O$

(8) $NO_2^- + O_2 \rightarrow 2NO_3^-$

(9) $NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2$

The bacteria responsible for nitrification are *Nitrosomonas* and *Nitrobacter* whereas a number of facultative organisms perform denitrification. These include *Pseudomonas*, *Achromobacter*, *Flavobacterium*, and *Bacillus*.[8] Algae assimilate nitrogen and phosphorus during growth but endogenous respiration of algae can contribute greatly to the oxygen demand of a wastewater system and the release of significant amounts of nitrogen and phosphorus which may cause accelerated eutrophication of surface waters.

Middlebrooks *et al*[10] reviewed several nitrogen removal models for application in aerated lagoons. They found the first order plug flow model to fit the test data reasonably well. A mathematical model developed by Reed[11] described nitrogen removal at various levels of temperature and pH. Separate rate constants were evaluated for 4°, 8°, and 24° C. Testing the model with Alberta data produced reasonably good results. Reed indicated the removal equation was applicable to any typical pond systems located in arctic, subarctic or temperate climates.

2.2.4 pH and Alkalinity

Stumm and Morgan[12] discussed the effects of aerobic respiration and photosynthesis on the alkalinity of an aqueous system. Qualitative effects of the various biochemical processes on alkalinity are summarized in Table 2.1.

Table 2.1 - Processes Affecting Alkalinity (after Stumm and Morgan[12])

Process	Alkalinity Change
Aerobic Respiration (no decomposition of NO_3^-)	No change
Photosynthesis (no assimilation of NH_4^+)	No change
Nitrification	Decrease
Denitrification	Increase
Sulphide Oxidation	Decrease
Sulphate Reduction	Increase

The evolution or consumption of carbon dioxide in an aqueous system does not change the alkalinity since no protons are involved. Thus, aerobic decomposition by heterotrophs will produce carbon dioxide, depressing the pH, without altering the alkalinity. Similarily, algal growth consumes carbon dioxide, raising the pH. Again the alkalinity of the system will remain unchanged unless the pH is elevated to the point where calcium carbonate precipitates reducing the alkalinity.[9] At pH values greater than 10, biological activity becomes inhibited. Algae autorespire at night, producing carbon dioxide, causing the pH to

drop.

It is essential, for efficient biological performance, to have sufficient alkalinity to buffer the diurnal variations in pH.

2.2.5 Natural Disinfection

Lagoon environs are hostile to many enteric organisms, both pathogens and non-pathogens. Mechanisms attributed to natural disinfection include sedimentation, sunlight, adsorption, predatory microorganisms, nutrient deficiencies, phages, biotoxins, algae, pH, and specific ion toxicity. Mitchell and Chamberlin'' found sedimentation and sunlight were significant in removing indicator organisms. Algal toxicity was related to sunlight. They discounted any contribution from biotoxins or phages.

Parhad and Rao'' found *Escherichia coli* died faster in the presence of algae and at a pH greater than 10. Others reported that algae have no significance in the removal of viruses or bacteria.'' '' It is likely that algae have little impact since *E. coli* are sensitive and would perish under conditions of high pH. McGarry and Bouthillier'' found the rate of *Salmonella* die-off related to the organic loading.

Virus removal has been attributed to adsorption to solids and subsequent sedimentation.'' ''

Bacterial removal kinetics are assumed to be first-order and various authors have applied chemical reactor engineering to model lagoon efficiency.[10] [11] A consistent problem has been the evaluation of the rate constant, K. Polprasert *et al*[4] used a regression technique to evaluate K. The parameters which were incorporated into the K model included organic loading, temperature, species, algal concentration, and ultraviolet light. They found the main effects on K were temperature, organic loading, and algal concentration.

2.3 PHYSICAL-CHEMICAL PROCESSES

A standard treatise on physical and chemical processes has been written by Weber.[12] It is this text which guides the review of these processes in sewage lagoons.

2.3.1 Sedimentation

This is the most important physical process operating in a lagoon and accounts for primary treatment.[13] [14] [15]

Four types of sedimentation have been classified.

1. Type I or discrete particle settling which is described by Stoke's Law under laminar conditions. In turbulent flow conditions, Newton's law applies.[13]

   This type of sedimentation deposits grit in the vicinity of the lagoon inlet where the flow velocity

decreases to essentially zero.[4]

2. Type II or flocculent settling of dilute suspensions is important in removing suspended solids from a sewage lagoon. The dispersed solids of various physical and chemical characteristics gradually flocculate as agglomeration occurs and faster particles overtake slower ones.[8]

   Type II sedimentation is strongly dependent upon depth and residence time for maximum clarification efficiency.[10,11]

3. Type III or hindered settling is usually found at the bottom of the water column where the suspended solids concentrations are much higher. It is a transition zone between flocculent sedimentation and the compression of the sludge zone.

   Oxygen uptake rate increases in this zone leading to the anaerobic conditions found in sludge deposits.

4. Type IV or sludge compression is a very slow process which occurs as a result of sludge consolidation as solids accumulate. Middlebrooks *et al*[4] noted that thick sludge zones are anaerobic and gelatinous in nature, being difficult to dewater as a consequence.

Sedimentation rate is temperature dependent and allowances should be made in detention time.[8]

From the foregoing it can be seen that Type II clarification is of interest in facultative lagoon performance.[10] Various

reports indicated consistent 40 to 70 percent suspended solids removals.[2] [3] [4] This corresponds to expected performance for primary treatment, but is inadequate to meet secondary treatment standards required by regulating agencies.[4]

2.3.2 Coagulation and Flocculation

The terms coagulation and flocculation describe the destabilization and transport processes involved in solids removal respectively.[6]

Following sedimentation, the very slow settling and colloidal particles remain in suspension due to their small size and high electrostatic charges.[6] [7] [8] [9] These will not settle unless converted to a form which will promote sedimentation. One approach is the use of biological treatment to convert this material into a biomass form which can be separated from the water column by sedimentation.[4]

Biological processes usually remove the colloidal material effectively except during periods of low temperature. Unfortunately, algae, which are a key component of the lagoon process, also contribute to suspended solids in the effluent and subsequently to BOD. In some cases further treatment is required prior to discharge into the receiving environment.[10] The methods for controlling algal mass are discussed in a later section.

A second approach to poorly settling solids is the use of chemical coagulants such as polyelectrolytes or metal salts.

These destabilize colloids through (i) charge neutralization, (ii) double-layer compression, (iii) sweep flocculation or (iv) interparticle bridging.[13] [14] Smith *et al*[15] stated that coagulation was a slightly temperature sensitive process in the range 0° to 30° C. Al-Layla and Middlebrooks[13] found a temperature dependence when coagulating algae with alum. This was attributed to a decreased solubility of aluminum hydroxide, improved adsorption, and reduced hydrophilic tendencies.

Flocculation depends on an energy input to promote agglomeration.[15] In the case of a facultative lagoon, this energy is provided by wind or thermally induced currents. Since transport through a liquid medium is involved, reduction in temperature increases the viscosity thereby reducing the overall rate of flocculation.[15]

Biological flocculation is an important mechanism, promoting adsorption and sedimentation.[16] [17]

Al-Layla and Middlebrooks[13] reported autoflocculation of algae at temperatures greater than 10° C in the presence of 100 mg/L of alum. This has not been studied in depth for lagoon applications. Chemical coagulation and flocculation are primarily of interest in effluent upgrading.

2.3.3 Precipitation

As with the previous process, precipitation has found its greatest use in upgrading effluent quality, particularly with

respect to phosphorus removal.[11,4] This is discussed in detail in a later section.

The theory of precipitation involves the conversion of a soluble species to an insoluble metal complex by the addition of chemicals.[9,2] Precipitation depends on the solubility product of the chemical species in question which varies with temperature and pH. Stumm and Morgan[9,2] provided a detailed account of coordination chemistry in aqueous systems and described several potential reactions which may occur in natural waters and the factors determining one reaction's preference over another.

Balmer[11,9] described three methods for chemical precipitation:

1. ahead of the lagoon in a separate facility;
2. following the lagoon in a separate facility; and
3. in the lagoon itself.

Our concern is with the third alternative, which contributes to sludge accumulation.

2.3.4 Adsorption

Adsorption is defined as the accumulation of materials at an interface or surface.[10,2] In lagoons, adsorption is a potentially important phenomenon which enhances the biolgical and physical processes, particularily coagulation, but lagoon research is sparse though it has been recognized by many authors.[5,6,10,2]

Algae and suspended solids absorb nutrients from the water column without necessarily stabilizing the organic matter.[8] Therefore, BOD is removed but the resulting biomass will require stabilization by either sludge digestion or a tertiary process.

2.3.5 Filtration

Filtration is a physical unit process which is not directly part of the lagoon but is frequently used following the lagoon to separate biological solids from the effluent. Three types have been studied.

1. Intermittent Sand Filters - Essentially slow sand filters which operate intermittently, separating algal mass and inorganic matter from the effluent. As the filter becomes clogged, it is removed from service and the clogged sand is removed.[120]

2. Rock Filters - Simply a filter bed consisting of rocks, 50 to 200 mm in diameter, through which the effluent flows. The interstitial spaces and surface area allow suspended solids to settle.[121]

3. Microstrainers - These devices consist of drums covered with 1 to 25 μm polyester or stainless steel fabric. As the drums move through the lagoon effluent stream, algae are trapped and then removed from the screening as it rotates from the effluent.[122] The predominant particle size determines the choice of mesh size.

2.3.6 Air Flotation

Flotation is a process in which the bouyancy of suspended particles is increased by the attachment of gas bubbles causing the particles to rise to the surface. This process may be used in conjunction with chemical coagulation and flocculation.[1,2,3] Two methods, autoflotation and dissolved air flotation, are used in wastewater treatment. Autoflotation occurs when an effluent is saturated with a gas, causing tiny bubbles of gas to be released which attach to flocculent suspended material, thereby floating the material to the surface.

Dissolved air flotation (DAF) is an extension of this process to undersaturated effluents where the waste stream is directed to a pressure vessel. Pressurized air is introduced into the effluent and when the pressure is released, minute bubbles are formed, attaching to nuclei of suspended material which then, due to a net bouyancy increase, float to the surface. The surface solids may then be skimmed and directed to sludge disposal facilities.

2.3.7 Aeration

The unit process of aeration is commonly used to accomplish two objectives:

1. increase oxygen levels; and
2. promote mixing.

Aeration has been examined in great depth for applications in activated sludge, extended aeration, oxidation ditches, and various types of aerated lagoons.[4, 9, 10]

2.3.7.1 Oxygen Uptake

The basic equation describing oxygen uptake is;

$$\frac{dC}{dt} = \alpha KLa(\beta C_s - C_o) - r_m$$

where;

KLa = transfer coefficient (1/s)

C_s = oxygen saturation concentration (mg/L)

C_o = desired oxygen level (mg/L)

r_m = microbial requirements (mg/L)

α, β = correction factors

Temperature influences C_s and r_m significantly, raising the former and reducing the latter.

2.3.7.2 Types

Aeration configurations are flexible, depending on the application. Three main types have found application in lagoons.

1. Surface aerators such as the Kessener brush and surface turbine are the most commonly used in lagoons since they require little infrastructure yet can produce impressive results.[1,4] Complete mixing is not usually accomplished with surface aerators.

2. Submerged turbine aerators combined with a sparger can provide high levels of treatment under completely mixed conditions. Some completely mixed aerated lagoons are designed with this type of aerator.[1,3]

3. Diffused aeration systems involve the supply of air through diffusers of various designs.[4] Diffused aeration produces a range of mixing conditions.

2.3.7.3 Power Requirements

All aeration devices require input of energy to produce the desired results. Surface aerators use approximately 1.0 kw.h/kg O_2 compared with 1.25 kw.h/kg O_2 for diffused air systems.[4]

2.3.8 Disinfection

Disinfection is the process of destroying or inactivating microorganisms.[1,2] A number of different disinfecting agents have been used including chlorine, ozone, ultra violet and gamma radiation, and heat.[4] The most commonly used compound is chlorine, due to its low cost and availability. Recently, there has been criticism of using chlorine as a wastewater disinfectant due to the formation of carcinogenic, trihalomethane compounds.[1,4]

With respect to lagoons, disinfection is used to remove microorganisms from the effluent when bacterial standards cannot be met.[4,7] Chlorine has been used in the past to accomplish this

and has been found effective in reducing suspended solids and BOD_5.[127] Ozone has been used to treat dilute, cold wastewater at the pilot plant scale with some success.[128] [129] The main disadvantages of ozonation are higher costs relative to chlorine and the requirement for on site generation of the product.[130]

2.4 LAGOON MODELS

2.4.1 Background

The purpose of simulating sewage lagoons is to enable the designer to determine the response of a lagoon to various operational and environmental conditions.

The problem with mathematical modeling of lagoons is that they are a complex "black box",[131] resulting in the use of deterministic or phenomenological models which tend to be location specific.[132] The development of sophisticated numerical models is relatively recent, being coincident with the evolution of computers.[133] However, since the processes in a lagoon are largely uncontrolled biological and biochemical reactions, a satisfactory, universally applicable relationship has not been developed.

2.4.2 Theory

Two approaches have been used in an attempt to simulate the lagoon process:

1. hydraulic theory; and

2. biochemical process theory.

In lagoon applications, the first is mechanistic and the second is phenomenological.

The following discussion will relate directly to aerobic and facultative lagoons since aerated lagoons are suspended growth processes, which have kinetics similar to the activated sludge process. A detailed development of the theory for this can be found in Grady and Lim.[5]

Anaerobic lagoons resemble conventional, low rate sludge digestors which have poorly understood kinetics.[134] Therefore these will not be considered.

Controlled, intermittent discharge lagoons have not been studied extensively. Only one report[135] was found on modeling these lagoons. It was an extension of the Ferrera and Harleman[136] model.

2.4.3 Biological and Chemical Kinetics

The complexity of the interactions of physical, chemical and biological processes within a lagoon thus far preclude systematic mechanistic analysis of the kinetics. An empirical approach usually prevails based on observations of existing systems resulting in first-order approximations for BOD removal, bacterial reduction, and nutrient removal.[66, 91, 131] The

development of numerical and analytical mixing models include this assumption. Rate constants are developed from past experience, laboratory and field studies.[132]

2.4.4 Hydraulics

It is generally believed that continuous discharge lagoons operate somewhere between completely mixed flow (CMF) and plug flow (PF) regimes.[137, 138]

The kinetics of PF and CMF reactors have been described in detail by Grady and Lim.[5] Watters *et al*[139] provided a very complete and detailed discussion of lagoon hydraulics and various approaches to hydraulic modeling, as did Middlebrooks *et al*.[47] A non-ideal flow model for chemical reactors was presented by Wehner and Wilhelm.[140] Ferrara and Harleman[136] noted that dispersed and combined flow models required a knowledge of input parameters which were obtainable from costly tracer studies while producing results marginally superior to the ideal CMF or PF models.

Chapman[141] reviewed techniques for determining lagoon mixing parameters from tracer studies and found non-linear regression to be superior to the usual linear least squares approach. Berthouex and Hunter[142, 143] described a method of designing experiments to determine first order rate constants accurately.

Ferrara and Harleman[136] found, through dye studies, that performance approximated CMF conditions and was greatly dependent

on the geometry of the pond, and the location of inlet and outlet structures. This was contrary to McKinney[44] who claimed that wind induced mixing was more critical than lagoon geometry. Their findings also contradicted Middlebrooks *et al*[47] who found PF conditions in lagoons. This is intuitively correct since the assumptions behind CMF are rarely satisfied in a facultative lagoon. This is further exemplified in the EPA design manual[48] where the CMF design gave inadequate results compared with PF and empirical methods.

2.5 CRITIQUE

2.5.1 Biological Processes

Three areas of interest are:

1. anaerobic digestion of lagoon sludge at low temperatures;
2. the role of psychrophilic microorganisms in lagoon treatment; and
3. natural disinfection mechanisms.

Anaerobic digestion of sludge has a great deal of impact on sludge accumulation in cold climate lagoons, where the rate of the process is greatly slowed at temperatures less than 19° C. Optimization of anaerobic processes in cold climates has not been studied.

Viable algae and bacteria are reported in freezing water and have been studied to a limited extent in activated sludge type processes. The reasons certain organisms are more active at low temperatures are not well understood.

Natural disinfection has been studied in some detail and temperature played an important role in bacterial inactivation. Low temperatures contributed to greatly reduced removal rates. Adequate models of microbial removal have not been developed due to the stochastic nature of lagoon environments and poor evaluation of the rate constant, K. More sophisticated evaluation techniques are required to improve the accuracy of K.

2.5.2 Physical-chemical Processes

Sludge accumulation and consolidation have not been studied extensively and are of concern in cold climate lagoons. The rate of accumulation has been sporadically monitored and problems of floating sludge blankets have been reported.

Bioflocculation has been observed but there has been little research on the topic. Other areas of interest are the sorption and disinfection processes.

The role of sorption in lagoons is believed to be of importance, influencing microorganism and nutrient removal. The processes involved are not well understood particularily under ice cover. More research is required in this area.

Disinfection of wastewater has been studied in depth and has many benefits and liabilities. Chief among the benefits is the removal of pathogenic organisms from the receiving waters and a reduction in ultimate BOD. Unfortunately, certain pathogens such as viruses, endospore-forming bacteria, and protozoal cysts are resistant to the usual chlorine disinfection process.

Other disadvantages of halogen disinfectants are the production of carcinogenic organic compounds (trihalomethane, chloroform) which may pose a potential health hazard to downstream users, and residual toxicity which inhibits fish and other natural fauna.

Of the oxidative disinfectants, ozone has been investigated as an alternative to chlorine since it is highly effective against all pathogenic organisms and apparently does not produce harmful by-products. Its major disadvantages are on-site generation and higher costs than chlorine. The relative merits of disinfection as an upgrading technique are discussed in Section 7.

2.5.3 Models

A satisfactory simulation model of the processes occurring in a lagoon is not available due to the complexity and dynamic nature of the lagoon ecosystem. The biological kinetics for various substrates in an ice covered lagoon have not been studied. First order models are used but little information exists on appropriate rate constants.

The dispersed flow model is the most feasible of the models based on chemical reactor theory since it is unlikely that ideal plug or completely mixed flow regimes occur in lagoons. In fact, CMF is unlikely to occur in facultative lagoons since the assumption of complete mixing is rarely fulfilled. Determination of dispersion numbers and reaction rate constants greatly reduce the applicability of this approach especially since the rate constants are virtually impossible to determine. It is concluded that a satisfactory hydraulic model has not been determined as of yet. Attempts at numerical models of individual biochemical processes have proved to be inadequate.

The value for the rate constant, K, is often quoted in the literature but its evaluation method is not usually described. Chapman, Berthouex and Hunter discussed approaches which improved the precision of parameter estimates using statistical methods but few engineers understand statistical analysis and these techniques are not utilized. Lack of precision in evaluating the rate constants can greatly influence the accuracy of these models.

3. FACTORS AFFECTING LAGOON PERFORMANCE

3.1 CLIMATIC INFLUENCES

The climate under which the lagoon operates exerts a great deal of influence on the performance. Lagoons have been used successfully from tropical to arctic climates but each exerts its own special effects which must be accounted for in the design.

3.1.1 Temperature

The single most important factor affecting lagoon performance is temperature.[1,3] It not only affects the physical, chemical and biological processes, but influences biological population distribution, water density, ice cover, and mixing.

As discussed in the previous section, biological and chemical processes within lagoons are approximated to first order kinetics of the form;

$$r = -K X_o$$

where;

r = reaction rate (mass/volume.time)

X_o= initial concentration of substance (mass/volume)

K = reaction rate constant (1/time)

Temperature effects can be related to K by the modified van't Hoff-Arrhenius equation;

$$K_t = K_{20}\theta^{t-20}$$

Here, K_t is the rate constant at any temperature above 4° C and K_{20} is the rate constant determined at 20° C. The coefficient, θ, relates the temperature dependence of mechanisms involved in the process under consideration. Evaluation of θ for sewage lagoons has yielded an average value of 1.077.[9] [10]

The use of this equation is questionable in cold regions since; (i) at temperature extremes relative to the reference temperature, θ is very inaccurate and (ii) the microbial population at 20° C is predominatly mesophilic whereas at 0° to 10° C psychrophiles predominate.[9] [10] The psychrophilic population do not follow a downwards extrapolation of mesophilic biochemical kinetics.[9]

Schneiter and Grenney[10] presented a mathematical model which purported to overcome the deficiencies of the van't Hoff-Arrhenius approach. Their equation took the form:

$$K_t = K_s f'$$

where;

K_t = rate constant at temperature (1/d)
K_s = rate constant at standard reference temperature (1/d)
f' = dimensionless correction coefficient at standard reference temperature

$$f' = \frac{(1+G_1\{\exp[\gamma(T_*-T_1)]-1\})\exp[\gamma(T-T_*)]}{1+G_1\{\exp[\gamma(T-T_1)]-1\}}$$

where;

G_1 = value of dimensionless temperature correction coefficient near the lower threshold temperature

T = desired temperature (°C)

T_* = standard reference temperature (°C)

T_1 = lower threshold temperature (°C)

T_m = upper threshold temperature (°C)

$\gamma = (T_m-T_1)^{-1}\ln[0.98(1-G_1)/G_1(1-0.98)]$ ($°C^{-1}$)

The authors provided a table of values for T_1, G_1, and γ for various elements of concern in water quality monitoring. (Table 3.1)

Table 3.1 - Some Values of T_1, G_1, and γ (after Schneiter and Grenney[1,2])

Parameter	T_1 °C	G_1	γ °C
Total coliform	2.0	0.1	0.1740
Fecal coliform	2.0	0.1	0.1740
BODU	2.0	0.1	0.1427
NH_3-N	1.0	0.2	0.1427
Dissolved oxygen	1.0	0.3	0.1281
Benthic algae	2.0	0.2	0.2639
Planktonic algae	2.0	0.2	0.2639

Microorganism die-off and biological kinetic rates decrease with temperature but the process is not well understood.[1,2,3,4,5] McKinney[4] stated that sudden changes in temperature kill the

algae population, whereas gradual changes tend to allow acclimatization.

Girling[53] observed nitrification at temperatures below 10° C which contradicted other findings.[39] Sutton[53] reported the results of a pilot study which indicated the feasibility of biological denitrification at temperatures as low as 5° C.

Oswald[57] found that sludge accumulated when temperatures less than 19° C occurred in the sludge zone. This was accompanied by a marked drop in methane production. Grady and Lim[4] reviewed the effect of temperature on anaerobic digestion and noted there was little information available. They pointed out that small changes in temperature may quickly upset the biological balance. They speculated that non-methanogenic bacteria were sensitive to low temperatures (< 15° C) and stopped metabolising organic matter.

The physical properties of water such as viscosity and density are changed by temperature. Maximum density of water occurs at 4° C which is an important factor in thermal stratification. Viscosity increases as temperature decreases, adversely affecting sedimentation and flocculation as discussed in Section 2.

3.1.2 Ice Cover

Ice cover is a consequence of extended periods of cold air temperatures.[4] [5] [6] It forms after lagoon water temperature has decreased below the temperature of maximum density. As the liquid temperature goes lower, the coldest water is at the surface and freezes into the less dense, solid form. Once the ice cover is established, surface reaeration is eliminated.[1] [3]

Many authors tend to discount the contribution of surface reaeration to the oxygen balance of a lagoon, attributing oxygenation to photosynthetic production by algae.[2] [4] [5]

Sidio *et al*[3] reported aerobic conditions under 300 mm of ice cover at a newly constructed lagoon in New England. He did not state the organic loading, however a significant population of viable *Chlamydomonas* was reported. Anderegg *et al*[8] also reported aerobic conditions under one metre of ice.

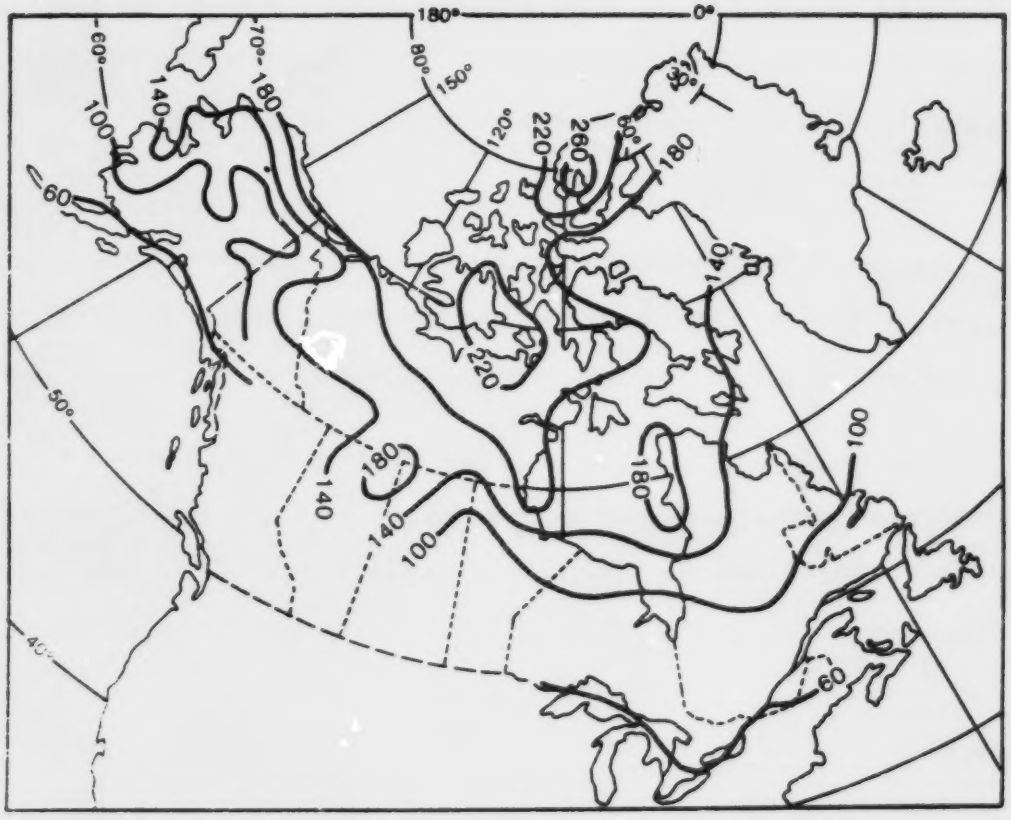
Sparling[10] referred to a report by Croxton, Thusman, and Shiffer of the Minnesota Academy of Science, where it was found that 33 percent of the incident light penetrated 350 mm of ice. The same investigators reported 0.27 percent of the incident light passed through 100 mm of snow.

Normally, ponds in the far north accumulate one to two metres of ice cover over the winter with varying amounts of snow cover.[11] [12] (Figure 3.1) The combination of rapid, algae killing temperature changes in the autumn and heavy ice cover accounts for the anaerobic conditions found in northern lagoons.

3.1.3 Snow Cover

Even with thin ice, any accumulation of snow reduces the light to near zero. This impacts photosynthetic reoxygenation adversely.[88] [63] [64] Snow cover also insulates the surface, reducing heat loss and subsequent ice thickness.

Figure 3.1 - Maximum Ice Thickness Observations (cm) (from Smith *et al*[88])



3.1.4 Thermal Stratification

Thermal stratification is a major problem with lagoons in northern regions and has been studied in some detail.[1,8] [1,6] [1,7] Short circuiting problems in continuous flow systems have been attributed to thermal stratification. Stratification occurs twice during a normal annual thermal cycle in a cold region lagoon:

1. during the period when the epilimnion is warmer than the denser, cold water below; and
2. during ice cover when the cold surface (< 4° C) water exists.

Entry of raw sewage into a lagoon which is at a different temperature also causes thermal stratification, which can lead to short circuiting of flow.[4] [1,6]

Thermocline position is a function of seasonal air temperature and light penetration which in turn is a function of turbidity and algal concentration.[1] [1,8]

The depth and area of a water body have been related to the formation of thermoclines by the relative depth which was defined as:[1,8]

$$D = 50\ D_o\ (\pi/A)^{1/2}$$

where;

D_o = depth of water body (m)

A = area of water body (m^2)

D = relative depth (m)

When D is large, the water body has a tendency to form a thermocline. The application of this to a lagoon is not reported however it is probably inappropriate since daily weather such as wind, temperature, or cloud cover will affect the stratification.

Oswald[37] found that no thermal stratification occurred in deep ponds in California due to the mixing action of gases produced from benthic decomposition. He noted that thermocline formation was beneficial to ponds in that it promoted a more even distribution of organic loading over the pond whereas cold, dense water would normally halt the warm sewage at the inlet, creating uneven loading conditions.

Major turnovers occur in the spring and autumn due to the change of surface water temperature past the 4° C point of maximum density.[46] The turnover eliminates thermal stratification and brings some of the previously deposited solids into the water column, increasing BOD and releasing odiferous gases previously trapped in the hypolimnion.[49] [58] [46]

The cold climate use of controlled discharge lagoons often does not take this into account and should be evaluated in terms of turnover occurrence to minimize adverse effects.

3.1.5 Wind

Wind fulfills two main functions; (i) to promote surface aeration and (ii) to promote mixing of the pond contents.[44] [49]

'[4] Wind may also be involved in short circuiting.[3]' [4]'

Some authors have emphasized the importance of wind in maintaining well mixed conditions in a lagoon and have generally agreed that pond design should promote wind access.'[5]'

Middlebrooks *et al*[4]' agreed with the principle of wind mixing to enhance lagoon performance, however they stressed that alignment of the lagoon inlet-outlet axis perpendicular to the prevailing wind direction was essential in reducing the effect of wind induced short circuiting.

3.1.6 Sunlight

Since photosynthetic oxygen production is of primary concern in a sewage lagoon, sunlight and light penetration is important.'[5]'

High latitudes, combined with heavy ice and snow cover, essentially eliminate the possibility of photosynthetic processes during the winter, however long hours of sunlight during the summer promote oxygen production.[4]'

During summer operation, light penetration is a function of algal concentration and can be estimated by the Beers-Lambert Law:'[4]'

$$I = I_0 e^{-k \times d}$$

where;

I = light intensity at depth, d ($erg/cm^2.sec$)

I_o= incident light intensity ($erg/m^2.sec$)

k = absorption coefficient (cm^2/mg)

x = concentration of algal cells (mg/cm^3)

d = depth (cm)

Algae have a variety of preferred light intensities therefore the aerobic zone will be dependent on the species present and intensity of light.[44]

The presence of strong ultra-violet (UV) radiation contributes to increased microorganism removal.[16] [45]

3.1.7 Water Balance

The water regime in a lagoon is dependent upon inflow, outflow, precipitation, evaporation and seepage. Of these elements, precipitation, evaporation and seepage have been reviewed below.[15]

Uncontrolled runoff which enters a lagoon causes a reduction in detention time, therefore efforts must be made to isolate the lagoon from adjacent drainage basins.[9] Lagoon systems which are connected to combined sewer systems should have provisions made for flow equalization to avoid hydraulic overloading during periods of precipitation.

Any body of water that has surface exposed to the atmosphere will experience evaporation.[9] Evaporation is climatically variable and some regions are able to operate ponds on the basis

of zero discharge.[47, 58] Evaporation may adversely affect lagoon performance by concentrating dissolved solids, inhibiting biological processes.[1, 47]

McLaren[170] summarized evaporation theory from small bodies of water. It was evident that the theory was difficult to apply because of high variation in wind speeds and water temperatures. Therefore regional experience should be used when accounting for evaporation in a design.

Exfiltration of lagoon liquid can have a detrimental impact on groundwater quality.[47, 58] In addition, if adequate depths cannot be maintained, nuisance conditions develop.[171]

The use of impermeable membranes as liners may be a necessary requirement as dictated by the soil conditions.

3.1.8 Sludge Accumulation

Sludge build-up in cold climates is well documented [27, 57, 172, 173] yet only recently has thorough research been carried out by Schneiter.[53, 67]

Sludge accumulation reduces lagoon volume, potentially leading to reduced detention times and a shorter operational life.

Schneiter found from a survey of 31 cold climate municipalities that 15 had total sludge accumulations ranging from less than 100 mm to greater than 600 mm. Alaskan aerated

lagoons were found to accumulate sludge at a rate of about 25 to 50 mm per annum. Middlebrooks *et al*[47] reported accumulation rates in Canada and Alaska ranged from 0.25 to 0.40 m^3/d.1000 people, the higher rate for sites at the highest latitude.

Anaerobic lagoons operated in the Prairie Provinces were reported by Clark *et al*[174] to accumulate sludge over the same range as the facultative lagoons above.

3.2 REACTOR INFLUENCES

The previous discussion dealt with climatic characteristics the designer has little control over, but which must be accounted for in the design.

This section deals with the design parameters the engineer can control. The use of these parameters will determine the performance of the lagoon regardless of the climate the lagoon is operating under.

3.2.1 Retention Time

Retention time is a critical factor in stabilizing organic matter and removing pathogenic organisms such as viruses.[11]

Lagoons have been characterized as short retention and long retention.[33] Short retention lagoons have times of 3 to 30 days. Long retention lagoons refer to those facultative, secondary lagoons with 30 to more than 220 day residence times.

The selection of a residence time for design of a lagoon has a great impact on the effluent quality with most jurisdictions setting the minimum residence time as a fundamental design requirement.[144, 178, 176]

The Province of Alberta requires 365 day retention for lagoons and Saskatchewan 180 days in recognition of the fact that only primary quality effluent is produced during the winter due to the lack of significant aerobic biological activity.

Only controlled discharge lagoons may be certain of obtaining full design retention times. All continuous flow regimes are subject to short circuiting with times ranging from 10 to 90 percent of the design retention time.[47]

3.2.2 Type of Lagoon

During the introduction to this report, four types of lagoons were defined:

1. aerobic;
2. facultative;
3. anaerobic; and
4. mechanically aerated.

Of these, facultative and anaerobic lagoons are of principal interest. Aerated lagoons are not applicable to remote, rural communities where low cost, simple operation and maintenance are

of foremost concern. Aerobic lagoons have not been used and are not feasible for year round use in northern Canada.

3.2.2.1 Facultative

Simply, a facultative lagoon has an aerobic surface zone and an anaerobic bottom zone. The aerobic portion is maintained by photosynthetic oxygen supplied by algae and surface reaeration. Anaerobic respiration occurs in the bottom layer, however this is markedly slower than the aerobic processes due to sub-optimum temperatures and bacteria with low growth rates.[1] [2] [3]

The succession of ice during the winter months eliminates surface aeration and subsequent snow cover reduces the production of photosynthetic oxygen to zero creating anaerobic conditions throughout the water column. The onset of this condition results in performance similar to simple sedimentation.[4]

3.2.2.2 Anaerobic

These ponds are designed as anaerobic fermentation basins and resemble single stage anaerobic digestors in principle.[1] [2] [3] They have been used effectively in the pretreatment of high strength wastes.[1] [2] [3] [7] [8]

Anaerobic lagoons in Canada operate at sub-optimum temperatures resulting in primary treatment by sedimentation. The conversion of settled BOD to cell mass, waste products, and energy is slow resulting in sludge accumulation. Short retention

pond effluent is dependent upon further treatment in a facultative lagoon with sufficient retention time to meet required effluent standards.

Anaerobic lagoons may also produce foul odours on a routine basis.[7,9]

3.2.3 Depth

Depths ranging from 0.2 to 6 metres have been employed depending on the type of lagoon.[1,4] High-rate aerobic lagoons are usually 0.2 metre deep[4] and anaerobic lagoons may be 6 or more metres deep.

Facultative lagoons are usually 1.5 metres deep when operating, however water level control is necessary when ice cover and sludge storage are considered.[8] In addition, Middlebrooks *et al*[10] reported that a relationship may exist between depth and hydraulic efficiency. Model studies suggested that as depth increased, hydraulic efficiency decreased. Consequently, biological conversion was diminished.

Anaerobic ponds are deep to ensure that entry of oxygen is restricted and that temperature remains relatively constant.[8]

3.2.4 Short Circuiting

Short circuiting describes the condition where residence times are less than designed. It is a serious problem in lagoons and has been found to be caused by poor geometry, inadequate

inlet and outlet structures, thermal stratification, ice cover, and wind.[37, 44, 134, 135]

The general response to short circuiting problems is to build multi-celled lagoons in series, which tend to improve the hydraulic conditions.[44, 100, 101] Baffles in the lagoon have been suggested and tried but there have been problems with ice during the winter.

Some authors reported that lagoon cell geometry has little effect on short circuiting and that wind induced problems are more important.[44, 47] Others suggested that short circuiting was caused by thermal stratification and wind may be only a surface phenomenon.[107, 113, 131]

Ferrara and Harleman[134] concluded that geometry of the lagoon influenced the dispersion and was a factor in obtaining completely mixed flow conditions. Middlebrooks *et al*[47] found that geometry has little impact on the hydraulics and recommended the use of rectangular ponds for ease of construction and efficient utilization of land. Their results indicated that a length:width (L:W) ratio of from 1:1 to 2:1 provided good plug flow conditions. Others recommended 3:1 maximum and shapes of any type to suit the topograghy.[103] Mangelson and Watters[103] recommended large L:W ratios to promote PF conditions.

3.2.5 Flow Control Devices

Middlebrooks *et al*[] tested various inlet-outlet configurations on models and found that a single bank discharge inlet opposite a single bank discharge outlet provided the best hydraulic conditions in a flow through lagoon. It was suggested thermal short circuiting could be overcome by using outlet structures which allow the operator to choose the position in the water column to place influent and discharge effluent. These findings were supported by Fair *et al*[] whereas others' recommended more centrally located discharge points.

3.2.6 Operating Methods

Several operating approaches have been developed in an attempt to improve the effluent quality of lagoons.

3.2.6.1 Configuration

Multi-celled lagoon systems operated in series have been used to reduce short circuiting and the suspended solids content of the effluent.[] [] Marais[] reported improved microorganism removal in serial lagoons. Zickefoose[] recommended series operation during the summer to reduce the algal content of the effluent.

He also recommended the use of parallel lagoons to reduce the organic loading on a lagoon system operated under winter conditions.

Dawson and Grainge[83] suggested using multiple cell lagoons to provide extra storage during maintenance operations such as sludge removal.

3.2.6.2 Discharge Mode

Continuous discharge is the normal operating mode in temperate climates since seasonal variations of effluent quality are small. Historically, many lagoons located in cold regions were designed for continuous discharge. Currently very few cold region lagoons are being designed on this basis.

Intermittent discharge is used regularily in Canada to compensate for the lack of treatment in the winter months.[83] This type of discharge is often regulated for spring and/or fall release to take advantage of the dilution water in the spring and the high quality effluent in the autumn.[84] The problem of "when to discharge?" was recently addressed by Hatcher[85] who suggested the use of hydrographs to determine discharge periods compatible with maximum dilution.

The total retention concept is not common in Canada. It consists of equilibriating the inflow with evaporation and seepage losses, resulting in no surface effluent.[87] Use of evaporation will concentrate suspended and dissolved solids which may affect the biolcgical processes.[

3.3 CHEMICAL AND BIOCHEMICAL INFLUENCES

3.3.1 Dissolved Oxygen Concentration

Dissolved oxygen concentration determines the rate and level of treatment since aerobic, dispersed growth processes are faster and less temperature sensitive than anaerobic processes. During the warm months, algal oxygen levels fluctuate daily, ranging from supersaturated conditions to severely depressed levels during the dark endogenous respiration periods. The onset of winter and ice cover reduces aerobic action. Anaerobic conditions may prevail throughout the winter.

Reduced oxygen levels from either organic overloading or reduced algal activity may contribute to odour problems and public complaint.

3.3.2 Microbial Population

Halvorson[33] found stabilization activity to be a function of the number of bacteria, the temperature of the wastewater, and the nature of the substrate. Eckenfelder'[34] believed the food:microorganism (F:M) ratio was the most influential parameter in determining process temperature sensitivity. A relatively high F:M ratio in lagoons due to low microbial populations, was purported to be responsible for reduced efficiencies.

3.3.3 Toxicity

Thirumurthi[8] presented a table outlining the concentrations of toxic organics that will cause a 50 percent chlorophyll reduction in algae resulting in decreased photosynthetic activity.

The anaerobic reduction of sulphates and sulphur containing organics results in the production of H_2S, mercaptans and other sulphides. Inhibition of algal activity will occur if the average sulphide concentration is greater than 4.0 mg/L.[9] Un-ionized H_2S is pH dependent and toxic to aquatic life at very low concentrations. The Ontario Ministry of the Environment has set an objective of less than 0.02 mg/L un-ionized H_2S for all receiving waters.

Grainge[10] learned that petroleum wastes were toxic to lagoon organisms, creating odorous conditions. This situation was alleviated by the installation of grease traps in garages.

The effects of ammonia toxicity on algae were investigated by Abeliovich and Azov.[11] It was found that ammonia at concentrations over 2.0 mg/L and at pH values over 8.0 inhibited *Scenedesmus obliquus*, a domininant species in high rate oxidation lagoons.

3.3.4 pH and Alkalinity

Alkalinity has two effects on a lagoon system. It is capable of buffering the aqueous system and it is a source of inorganic carbon for autotrophic organisms such as algae. If alkalinity is too low (a level not specified in the literature), there may be insufficient carbon dioxide available for algal metabolism inhibiting photosynthesis.

High pH induced by photosynthetic action may cause reductions in alkalinity by calcium carbonate precipitation. This could be of potential significance in some areas of the north where low alkalinity water occurs. This type of problem is related to the bedrock geology, where igneous and metamorphic regions have little buffer capacity in the surface waters whereas sedimentary basins have adequate alkalinity to ensure good buffering. The high diurnal variations of pH observed in southern lagoons have not been observed in the north, even though the buffer capacity of the water is lower. This phenomenon has not been explained.

Zooplankton mortality has been found to be correlated to high pH values.[88] However, the pH values observed to kill zooplankton were higher than would normally be observed in lagoons.

Means of controlling pH in lagoons were explored on a bench model by Pipes.[89] Feeding the influent sewage to lagoons during lighted periods, reduced the maximum pH somewhat. Reducing the pH

of the influent sewage definitely reduced the maximum pH for short detention times. Lowering the pH of the influent wastes also increased BOD removal for short detention times.

3.3.5 Organic Loading and BOD

Several investigators commented on the unsuitability of the standard five day, 20° C biochemical oxygen demand test[19] ($BOD_{5,20}$) for routine analysis of cold wastewaters.[47, 48, 49] The 20° C incubation temperature is unrepresentative of naturally occurring conditions and does not determine the oxygen demand of psychrophilic bacteria which are killed at temperatures above 10° C.[4] Gordon[47] recommended using the actual receiving water for dilution and having the incubation temperature at or near the receiving water temperature.

Organic loading is measured as mass of $BOD_{5,20}$ applied on an areal basis. Units are usually kg BOD/ha.d. Past practice has been to use the five day BOD determined at 20° C, for design in all climates. Evidence of different methods of substrate uptake in psychrophiles[4] suggested there may be a different ultimate BOD at low temperatures. This area has not been researched.

3.3.6 Odours

Odours are usually observed during spring breakup before aerobic conditions prevail. Fisher *et al*[19] found, after examining data in Alberta and Saskatchewan, that odours were probably related to high sulphate concentrations in the municipal water

supplies. It was noted that in all cases of severe odours, the sulphate content was greater than 400 mg/L. Sulphide production in laboratory scale ponds was studied by Gloyna and Espino.[88] They produced a regression equation relating organic loading and retention time to the production of sulphide. It took the form:

$$S^{2-}(mg/L) = \{1.058x10^{-4}L - 1.655x10^{-3}T + 0.0553\}\ SO_4^{2-}\ (mg/L)$$

where;

T = detention time in days, at 25° C

L = BOD loading in kg BOD_5/ha.d

This enabled them to estimate the average 24 hour sulphide concentration in a facultative lagoon at 25° C. Temperature effects were not considered. It should be noted that this regression equation is empirical and may not be applicable to cold region lagoons.

3.4 CRITIQUE

3.4.1 Climatic Influences

It is inevitable that temperature is of the foremost concern when discussing climatic influences on cold region lagoons. The algorithm proposed by Schneiter and Grenney[48] should be used for temperature corrections to process rate constants in lieu of the traditional modified van't Hoff-Arrhenius equation since the corrections are more accurate at the lower threshold

temperatures.

It is generally agreed that biological activity is reduced in cold environments, however, there is evidence that it does not stop completely under aerobic conditions.[9] [14]

The main source of dissolved oxygen is photosynthetic production by algae. The important factors to consider are:

1. maintenance of a viable algal population; and

2. maximizing light penetration during winter conditions.

As McKinney[14] pointed out, rapid temperature changes in the autumn kill the algal population. Consequently it is desirable to determine a method which will promote a gradual change in temperature allowing different populations to become established.

Anaerobic digestion is greatly reduced at psychrophilic temperatures therefore stabilization of organic wastes is essentially stopped over the winter months.[3] [9]

Summer conditions are similar to those in temperate regions. There is a large body of literature describing lagoon operation under these conditions.

3.4.2 Reactor Influences

The experience obtained over 40 years of operation in Western Canada has led to the use of the retention time criterion as basis for design. This recognizes low stabilization rates

during the winter months which are responsible for poor quality effluent at a time when receiving waters have their lowest assimilation capacity.

The mode of operation becomes of paramount importance since discharging lagoon contents at the wrong time of the year may have a detrimental effect on the environment.

Seasonal discharge lagoons are well known in Western Canada. In the past, two discharges per year have been carried out. One in the spring during peak dilution and a second one in the fall when contents are most stabilized. Alternatively, a single discharge may be carried out in the autumn.

It is important to carry out these operations before the thermally induced turnover occurs, a practice not always adhered to by lagoon operators.

Total retention systems have not received much use in Canada since ice cover precludes evaporation. In addition, little information is available on predicting evaporation rates in cold climates. This method needs further study since locations where effluent disposal options are limited could make use of this approach.

The location of inlet and outlet structures, associated piping and valves, is simplified by the use of controlled discharge lagoons. Short circuiting ceases to be a design consideration, allowing the designer flexibility in choosing central or bank feed depending on soil and other site conditions.

Inter-pond transfer and location of the drawdown pipe in the water column must be considered carefully to take advantage of the highest quality water.

3.4.3 Chemical and Biochemical Influences

High levels of pH will reduce the alkalinity in a lagoon system by precipitating $CaCO_3$ and may also inhibit biological activity. The naturally occurring low alkalinity levels in the north may not provide adequate buffer capacity to prevent wide variations in pH which may also inhibit biological activity. Low alkalinity levels could contribute to substrate limited growth of algae, inhibiting photosynthesis.

Anaerobic conditions contribute to odour problems and slow stabilization rates. Consideration should be given to organic loading to reduce this problem.

Dissolved solids may inhibit biological activity during periods of heavy ice cover, but this has not been well documented.

4. PROCESS DESIGN

4.1 INTRODUCTION

The U. S. Environmental Protection Agency report[44] entitled Design Manual: Municipal Wastewater Stabilization Ponds, summarized all of the currently used methods for designing lagoons. It provided examples of lagoon design but left the choice of method to the designer's discretion. Four basic approaches have been used to date for the design of sewage lagoons;

1. retention time;
2. organic loading;
3. empirical models; and
4. analytical models.

As discussed earlier, the main concerns of this review are facultative lagoons since anaerobic processes in cold climates have negligible effects compared with aerobic processes.[3] Middlebrooks *et al*[3] provided an excellent summary of design approaches and resulting performances.

4.2 RETENTION TIME

McKinney[44] stated that retention time is the main design criterion for lagoons operated in cold regions, setting a range of 120 to 150 days. Dawson and Grainge[43] recommmended 180 to 365 day retention for lagoons in the arctic and sub-arctic. McKinney also noted that the surface loading rate is established by this criterion if depth is maintained constant.

4.3 ORGANIC LOADING

This is the oldest criterion for sewage lagoon design and over the years, experience has produced the surface loading rates which are commonly used in temperate climates.[43]

Canter *et al*[42] reported typical BOD_5 loading rates across the United States demonstrating a trend towards reduced loading and longer retention times at higher latitudes. They recommended 22 kg BOD_5/ha.d as a maximum for regions with seasonal ice cover. Dawson and Grainge[43] supported this value as a criterion for northern Canada. Design by surface loading rate establishes the mean hydraulic residence time.

The EPA design manual[44] tabulated designs based on the approaches introduced above and found that areal organic loading from 11 to 22 kg BOD_5/ha.d to be as reliable as any of the rational models when sizing a lagoon for regions where ice cover forms. However, this approach has failed to meet effluent standards under continuous flow conditions in cold region

lagoons.[3,4]

4.4 EMPIRICAL MODELS

Three empirical models for BOD_5 removal in a continuous discharge system have been discussed in the literature.[2] [3] [4] These are:

1. the McGarry and Pescod regression equation;[3,4]
2. the Larsen equation;[3] and
3. the Gloyna method.[3] [4]

4.4.1 McGarry and Pescod

This equation was found to be of little use[3,4] particularily since its limiting criterion is for loading of 30 to 500 kg/ha.d which is never realized in northern lagoons. In addition, they do not account for temperature or pond depth which are both known to be of importance in lagoons.

4.4.2 Larsen

Larsen considered a number of environmental factors while studying lagocns in New Mexico and produced an empirical formula which has been found to be of no use in general applications.[3,4]

4.4.3 Gloyna

Of the empirical equations, this one has found the most acceptance since it is easy to use and accounts for the parameters considered to be of importance. It has the form;

$$A = 3.5 \times 10^{-4} Q L_o \theta^{(35-t)} f' f$$

for the depth of 1.0 metre.

where;

A = surface area (m^2)

Q = flow rate (m^3/d)

L_o = ultimate BOD (mg/L)

θ = temperature correction coefficient

t = temperature (°C.)

f = algal toxicity factor (usually 1.0 for domestic sewage)

f' = sulfide demand factor (1.0 for SO_4^{-} < 500 mg/L)

In testing this equation on cold region lagoons, Finney *et al* [44] found the results to be erratic and suggested the lower light intensity of the northern latitudes may have been a factor since Gloyna developed the equation in the southwestern United States.

4.5 ANALYTICAL MODELS

Analytical models have been reported in the literature since the mid-1960's. The major contributors being:

1. Marais;[101] [134] [137]
2. Oswald;[104] [105] and
3. Thirumurthi.[138] [104] [107]

Recently, Fritz *et al*[133] attempted a dynamic, biochemical model using 12 ordinary, first-order, linear differential equations to predict effluent characteristics. The results showed promise but were not useful.

Saunders and Minchew[133] and Hatcher[104] produced models of controlled discharge lagoons. Both used complex mathematical models which preclude use on a routine basis. Their application to cold climate lagoons is not foreseen.

The design applications of the theories introduced in Section 2 are presented below. It is intended as a summary of the literature and for detailed design procedures the reader is directed to the original reference.

4.5.1 Marais

Marais[134] presented three models in 1970 based on completely mixed flow (CMF) and first-order reaction kinetics.

Model 1

$$\frac{S}{S_o} = \frac{1}{(Kt+1)}$$

where;

S = effluent concentration (mg/L)

S_o = influent concentration (mg/L)

K = first order rate constant (1/d)

t = mean hydraulic residence time (d)

No temperature corrections were made.

Model 2

This model was the same as Model 1 except the modified van't Hoff-Arrhenius equation was used to correct K for temperature. He used the value of θ determined by Suwannakaran,[44] 1.085.

Model 3

The final model included a term for benthic oxygen demand. Since the parameters for benthic decomposition are normally difficult to determine, this model has not been used in design practice.

Marais and Capri[37] extended the model to a series CMF reactor which took the form:

$$\frac{S}{S_o} = \frac{1}{(Kt_n+1)^n}$$

where;

t_n = individual cell residence time (d)

n = number of cells

$$t = t_e \times n$$

Marais[9] used it in a later study for predicting the removal of indicator microorganisms from oxidation ponds in South Africa. The effects of thermal stratification and non-ideal flow created problems in predicting accurate numbers of coliform organisms but Marais concluded that a kinematic model was still of use in determining the relative merits of changes to a system, such as adding an extra cell.

The previously noted EPA design manual found this method to be the least satisfactory approach for sizing a lagoon.

4.5.2 Oswald

The Oswald method was developed for aerobic oxidation ponds in California and based on the principle of matching organic loading with algal oxygen production.[4] [5] This approach required a knowledge of biochemical reaction stoichiometry and the efficiency of solar energy conversion by algae.

These factors plus the variability of seasonal sunshine make this a difficult method to use.

4.5.3 Thirumurthi

Thirumurthi favoured the approach of dispersed flow in chemical reactors introduced by Wehner and Wilhelm.[100] The general equation has the form;[38]

$$\frac{S}{S_o} = \frac{4a \exp[1/(2d)]}{(1+a)^2 \exp[a/(2d)] - (1-a)^2 \exp[-a/(2d)]}$$

where;

S = effluent concentration (mg/L)

S_o = influent concentration (mg/L)

$a = (1+4Ktd)^{1/2}$

K = rate coefficient (1/d)

t = mean hydraulic residence time (d)

d = dimensionless dispersion number

It can be seen, as d approaches zero, the equation follows ideal plug flow (PF) theory. Conversely, as d approaches infinity, the CMF model is obtained. Metcalf and Eddy[4] provided a design example illustrating the use of the design nomographs presented by Thirumurthi.

As with the Marais approach, this model can be used with any first order reaction provided the rate constant K is known with some precision. The other key factor is the dispersion number, d. This is necessarily evaluated using tracer studies in ponds with similar geometry to the one being designed. The value for d has been found to range from 0.06 to 1.71 in lagoons.[78 100 97]

Some investigators have tested this approach on existing cold region lagoon performance data in the northern United States but have obtained poor correlation with the observed data.[34, 35] This was attributed to short circuiting and poor evaluation of the overall BOD_5 removal rate constant.

4.6 CONFIGURATION

Single cell or multi-cell? Series or parallel? These are important questions to be asked in the early stages of design.

First, from the theory of series CMF reactors[3] as the number of cells in series increases the flow regime approaches plug flow conditions. Superior performance has been reported from series operation of lagoons.[34, 37, 49, 50] Finney *et al*[50] compared the performance of three celled lagoons with a seven celled lagoon for a number of months. Over the period of the study, the seven celled lagoon was found to perform the best, never exceeding the secondary effluent BOD_5 standard of 30 mg/L. The three celled systems failed to meet the effluent requirements during the winter months. In another study in South Africa, Marais[50] reported higher microorganism removal in multi-celled lagoon systems.

Controlled, intermittent discharge facilities were considered an upgrading method by Middlebrooks *et al*.[47] Using serial lagoon configurations for intermittent discharge systems allows phase isolation with a number of benefits which have not

been considered in depth:

1. the design population may not be reached for several years, therefore by building small cells as required, the development may be staged over a number of years, reducing the financial burden on the community. Of course, mobilization and construction costs in remote areas may nullify any savings by using this approach.

2. if all cells are built at one time, they can be filled in stages, with the oldest being discharged as the system approaches capacity. Once this occurs, the feed is directed to the empty pond and the routine is repeated as necessary. One further advantage is that accumulated sludge can be removed from the empty lagoon without disrupting the facility.[83]

3. only the quantity of effluent required for the next storage cycle need be discharged.[47]

4.7 CRITIQUE

Of the approaches available to the designer of cold region lagoons, retention time criterion is the best since little stabilization occurs over the winter months. The practice of twice yearly discharge should be considered carefully since the spring discharge effluent consists primarily of settled sewage and may contain large numbers of pathogenic organisms.

It appears that autumn discharge of lagoon effluent is desirable since stabilization of organic matter and microorganism removal are at optimum levels. The timing of discharge should account for fall turnover and algae die-off and detailed discharge procedures should be included in the overall design package.

Organic loading criterion has limited use in continuous flow, cold climate lagoons where it has been demonstrated to be a poor basis for design if used improperly. However, experienced designers who are familiar with local conditions may still produce adequate designs on this basis. As noted by McKinney, once retention time is set, organic loading is established when depth is held constant.

The analytical and empirical models for continuous flow systems have application in Canadian lagoons only for the summer operation period where this mode of operation is used. Of the available approaches one has not been found to be superior. However, there is evidence that CMF does not occur in facultative lagoons and this approach should not be used. As discussed in an earlier section, other deficiencies may be attributed to lack of sophisticated analysis by engineers and designers. Also, severe winter conditions cannot be accounted for in the models.

McKinney's recommendation to use retention time criterion for cold climate lagoons is felt to be the best for now, since it is simple to regulate and provides reasonable treatment levels.

5. FACILITY PLANNING, DESIGN, AND CONSTRUCTION

5.1 INTRODUCTION

Once the lagoon has been chosen for the reasons given in Section 1 and the process sized and designed, the physical facility must then be planned, designed, and constructed to complete the wastewater treatment system.

A recent monograph edited by Johnston[1,8] entitled, PERMAFROST: Engineering, Design, and Construction was an excellent compendium of northern geotechnical engineering. It compiled data of interest to cold climate lagoon designers including engineering characteristics of frozen soils, ground thermal analysis, cold regions project planning, cold regions earthwork, and the design of dams and reservoirs in cold regions. A second document of interest to environmental engineers was the "Cold Climate Utility Delivery Design Manual"[1,8,9] which provided details on planning, designing, and constructing municipal engineering projects in the north.

5.2 PLANNING

5.2.1 Site Selection Criteria

The location of a community or industrial development usually determines the general location of a proposed sewage lagoon. Detailed siting of a lagoon follows a systems approach,

where a set of criteria is used to differentiate between various site alternatives. A tabular summary is provided in Table 5.1. Other pertinent site selection criteria are:[8]

- population and town growth patterns;
- proximity to the townsite;
- type of wastewater collection system;
- flexibility of effluent disposal methods;
- flexibility of the lagoon configuration;
- archaeological releases; and
- land use permits.

Criteria of importance in locating a lagoon in cold climates are the geotechnical conditions, the impact of the impoundment on the existing soil thermal regime, the impact of the lagoon on the hydrology of the area, access to the site for construction and maintenance, and access to the lagoon effluent receiver.

5.2.2 Geotechnical Considerations

The selection of a lagoon site depends on the permafrost conditions and soil properties which will ensure a stable earth structure.

Table 5.1 - Project Planning Considerations (from Johnston[33])

A. *Type of Project*

(1) *Linear*
- Highway
- Railway
- Pipeline
- Power line

(2) *Areal*
- Townsite
- Airport
- Dam, dyke
- Tank farm
- Borrow pit

(3) *Individual Structures*
- Building
- Tower
- Bridge, wharf
- Stockpile

B. *Project Information Required*
- Size and location
- Natural physical conditions
- Magnitude and type of loading
- Design life (temporary or permanent)
- Tolerance of movement (total and differential)
- Ancillary works or structures
- Cost and time limitations

C. *Site or Route Information Required*

(1) *Terrain*

(a) *Relief*
- Topography
- Slope (degree and orientation)
- Features
- Vegetation cover

(b) *Hydrology*
- Drainage (surface and subsurface)
- Water bodies
- Groundwater
- Stream flow
- Flooding
- Ice jams
- Icing

(c) *Geology and Soils*
- Surface and subsurface geology
- Ground ice
- Thermal regime (temperature profiles)
- Engineering properties (soil and rock)
- Construction materials

(2) *Climate*
- Temperature
- Precipitation
- Wind
- Snow drifting

(3) *Environmental—Social Impact*
- Land, water, air, noise
- Wildlife (animals, fish, birds)
- Local people

(4) *Logistics*
- Project scheduling
- Transportation facilities
- Access to and on site/route
- Summer and winter roads
- Local labour, materials and equipment available
- Equipment and transport costs

(5) *Economics*
- Time and money available

The term permafrost was defined by Johnston[199] as "the thermal condition in soil or rock of having temperatures below 0° C persist over at least two consecutive winters and the intervening summer". Permafrost occurs as three different types; continuous, discontinuous, and sporadic which are described in terms of increasing mean annual ground temperature. Continuous permafrost ranges from -5° to -15° C and discontinuous from a fraction below 0° C to -5° C. Permafrost has also been called "cold" (< -4° C) and "warm" (-4° to near 0° C).[199] Sporadic permafrost occurs where climate and terrain allow.[199] The distribution of permafrost in Canada is shown in Figure 5.1.

Figure 5.2 illustrates the typical "trumpet" curve of the ground temperature regime in a permafrost region. Only the monthly mean minimums and maximums are shown by the curve. A shallow depth of frozen ground thaws each summer to form an active layer whose thickness varies with climatic conditions. Brown[200] discussed in detail the factors influencing the active layer depth.

Figure 5.1 - Permafrost Distribution in Canada
(from Smith *et al*[13])

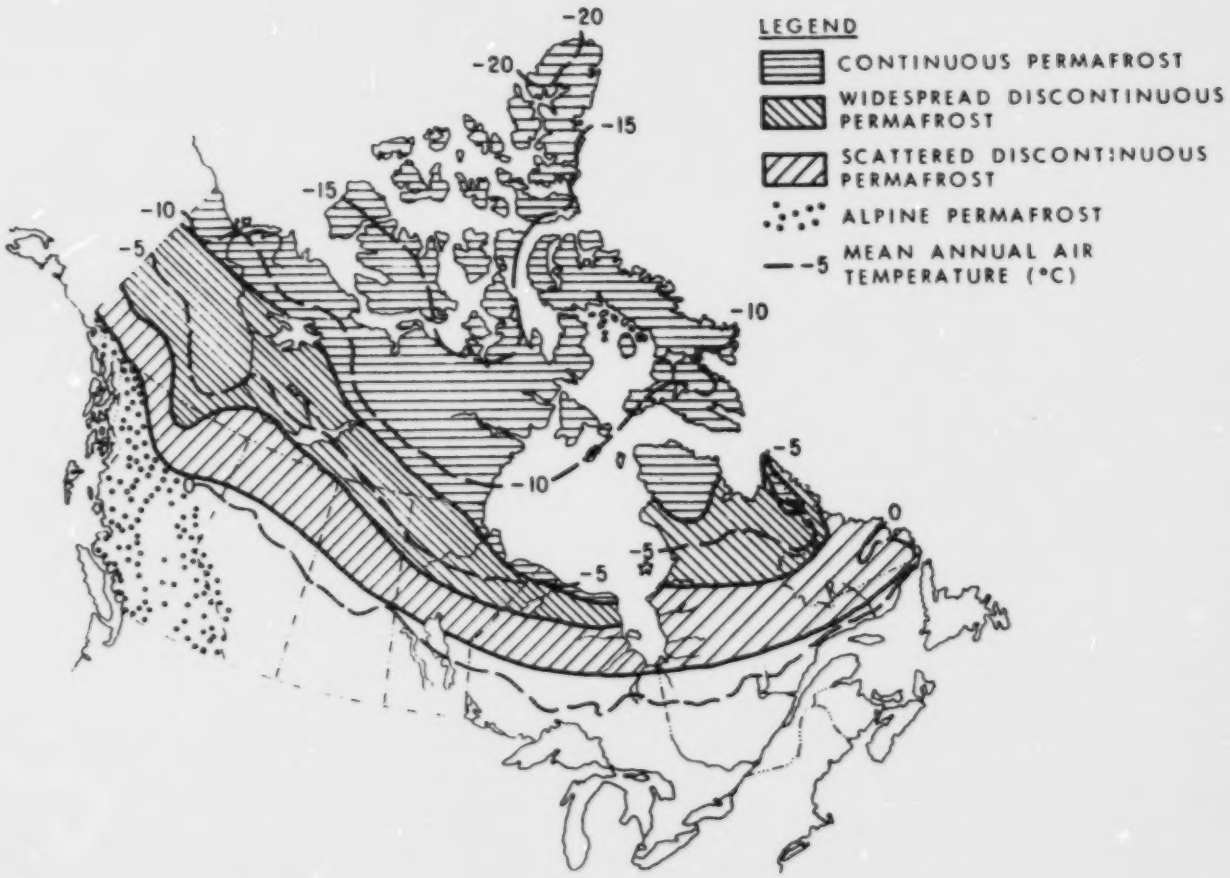
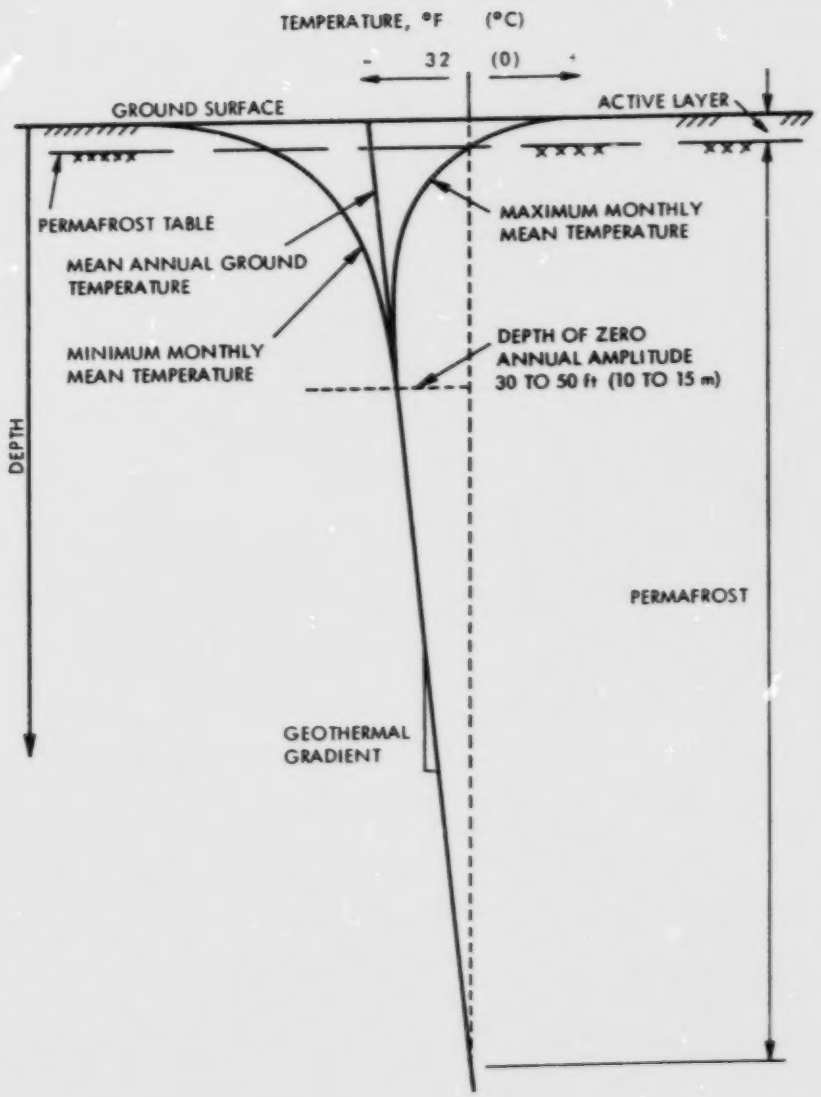


Figure 5.2 - Typical Ground Temperature Regime in Permafrost (from Johnston'''')



Frozen soil typically has substantially different properties of strength, deformation, and permeability from those of unfrozen soil.[1,2] The soil grain size distribution has important influence on the consequences of changes in the ground thermal regime caused by lagoons. Many frozen sands and gravels have limited amounts of ice contained within their pore space which results in no adverse behaviour if subjected to thawing conditions. On the other hand, ice-rich silts and clays are undesirable in the thawed state since the excess water which may result, creates high pore water pressures producing unstable soil conditions. Fine-grained soils are acceptable if permafrost is missing such as in areas adjacent to large rivers, lakes, or the ocean where the heat transfer has caused soils to thaw. These soils are also acceptable if it can be demonstrated that upon thawing, the finer grained soils do not generate excess pore water pressures.

A general knowledge of soil types and ground thermal regime is necessary to aid the planner in choosing the appropriate site. Preliminary information can be obtained from aerial photographs and special information maps available from various government agencies. A detailed field study by competent geotechnical specialists is mandatory prior to the final decision on site location. Table 5.1 outlines the various considerations that must be addressed in carrying through the field study.

5.2.3 Hydrology

5.2.3.1 Groundwater

Groundwater occurs in three forms in permafrost regions; sub-, intra-, and supra-permafrost.[19] The first two types are not normally of interest since surface water has no access except under special circumstances. Water from the active layer (supra-permafrost) may enter the berms during the summer period through capillary action creating increased moisture contents in the berm material. This will lead to changes in the thermal properties of the berms and in the long term, may alter the conditions so that instability may develop. During freezing periods this may contribute to frost heave in the lagoon berms.

Although frozen ground exerts a retarding influence on groundwater flow, it should not be considered impermeable. Soils may contain air, liquid water, ice, or a mixture of ice and liquid water therefore permafrost should be considered as a confining bed of low but finite permeability.[20]

The organic surface material has an important role in determining the drainage pattern at a given site. In the thawed state, due to the high hydraulic conductivity of the organic surface layer, available surface water infiltrates the upper layer. Factors which govern whether the water will continue downward into the mineral soil include:

1. hydraulic properties of the mineral layer; and

2. the rate of infiltration into the organic layer.

During the summer, the organic surface material is similar to a shallow aquifer confined by the underlying mineral soil which may be relatively impervious. This is particularly true if the active layer is thin where the organic surface layer acts as a conduit, moving the groundwater rapidly downslope.

5.2.3.2 Surface Water

Peak flows occur in northern rivers during the spring thaw creating hazards to treatment facilities located on the flood plain. Flood plain determination is necessary, to safely locate a lagoon above maximum water levels. This applies to lakeside facilities where ice and high water may damage structures. Oceanside lagoons must account for high tides caused by storms.

Surface drainage should not be interfered with at the site since thermal degradation may be accelerated by the combination of ponded water and warmer ground temperatures which occur beneath water bodies.[40]

The flow patterns of streams in the north are greatly influenced by the thickness of the organic material within their drainage basins.[202] Since this material is an aquifer of the surface water, the location of the surface drainage and quantity of water is controlled by the organic material.

5.2.4 Effluent Disposal Considerations

The end result of wastewater treatment is a treated effluent and organic sludge. Metcalf and Eddy[4] and Smith *et al*[18] outlined various disposal alternatives:

1. dilution in large bodies of surface water such as;
   - streams;
   - rivers;
   - lakes;
   - estuaries; and
   - oceans.
2. groundwater recharge (seepage pits);
3. wetlands;
4. land;
5. evaporation; and
6. landfill.

When choosing a lagoon site, the effluent disposal method must be considered carefully to optimize the selected option and to obviate the need for costly pumping, forcemains, and outfall structures.

The final destination of the effluent must be assessed to ensure that the downstream users are not unwittingly subjected to potential public health hazards. Persistence of microorganisms, poor mixing characteristics of bank discharges, and groundwater migration may create serious health hazards if not accounted for in the planning process.

5.2.4.1 Surface Waters

High flows in the spring and summer may cause adverse conditions at the outfall due to ice scour and floating pieces as the ice moves downstream. Hydraulic factors such as adequate rate of discharge during high flows is another consideration which must be anticipated by the designer during the planning stage. Wind blown ocean pack ice may make the use of special, costly, marine outfalls necessary.

Erosion of river banks and unstable soil conditions combine to cause inopportune failures in the discharge line at the outfall location. This cannot be tolerated in remote communities where the service infrastructure is not established to repair the failure.

Full advantage should be taken of the dilutional capacity of the receiving waters by ensuring the discharge point is located where natural mixing is optimized.

In permafrost areas, care must be taken to recognize the potential impact of thermal degradation along outlet channels.

Increased flows will accelerate erosion and the thermal regime of the channel may become impaired due to thermokarst.

5.2.4.2 Groundwater Recharge

The location of a lagoon, the soil conditions, and the type of groundwater will determine if groundwater recharge is a viable alternative at locations where surface water disposal is not possible. However, there is little published literature on groundwater recharge using seepage pits or wells in cold climates. Smith *et al*[18] mentioned this method and warned of groundwater contamination by microbes and nitrates.

5.2.4.3 Wetlands

This method of effluent disposal has shown some promise in the north but few detailed studies have been carried out. The proximity of a swamp or wetland to a townsite and lagoon should encourage consideration of this method. The extent of the wetlands use (trapping, hunting etc.), and potential public health impact should be considered prior to using this method.

5.2.4.4 Land

Smith *et al*[18] provided some information on land disposal systems. Many areas with continuous permafrost are unsuitable, particularily where fine-grained soils are present. This should be reviewed during the field geotechnical investigation program. Sletten[203] suggested that thawed areas adjacent to major water

bodies may be suitable for land application since permafrost is deep or absent. The impact of this on the quality of the adjacent water body should be assessed during the planning stage.

5.2.4.5 Evaporation

Smith *et al*[9] remarked that scientific data was lacking to adequately assess evaporation as an alternative in the north. The lagoon may require a very large surface area and cause problems in land acquisition and unjustifiable capital costs. If evaporation is considered, detailed analysis of several years of evaporation data is necessary to adequately design the facility.

5.2.4.6 Landfill

Cold climate lagoons accumulate sludge as noted in Section 3. Lagoons which are not designed to store sludge may require periodic cleaning, therefore suitable removal, storage for dewatering, and suitable dumping areas should be considered. However, this is not a high priority concern for new lagoons which are properly designed.

5.2.5 Access

Attention must be given to site access during periods of:

1. site investigation;

2. construction;

3. operation; and

4. maintenance.

Access by heavy equipment to the site from barge landings or airfields should be considered. This may result in restrictions being placed on the size and quantity of equipment and the time of year in which to carry out the site investigation and lagoon construction.[204]

5.3 DESIGN

5.3.1 Geotechnical Consideratons

The investigation program should consist of an office study of available information related to the geology and topography, vegetation, groundwater condition, climate, logistics, and environmental impacts followed by a detailed investigation of the ground thermal regime and the engineering properties of the frozen and unfrozen soils.

5.3.1.1 Sampling

Johnston'[18] detailed the overall site investigation program. Soil sampling and testing is carried out using the same standard procedures used in warmer regions.[205] Care must be taken to obtain high quality samples so that representative strength and permeability values for the soil types can be determined.[206]

Test pits are a very useful component of a field investigation. They can provide information on soil ice conditions, ease of excavation, and groundwater conditions. In addition, *in-situ* infiltration tests can be conducted if the soil is not frozen.

Temperature measuring devices such as frost tubes and thermistors installed at the site will give information on the depth of thaw and the soil temperatures as a function of depth and time throughout the various seasons. This will identify the frozen thermal condition and the location of unfrozen soils.

5.3.1.2 Soil Description and Conditions

The samples should be described in the field using the classification system for frozen soil suggested by Linell and Kaplar.[20] It consisted of three steps:

1. the Unified Soil Classification System, outlined by the U.S. Army Corps of Engineers, is applied to describe the soil phase. No mention was made of its frozen state.

2. the characteristics of the soil resulting from being frozen were described. This included a description of the ice, whether or not visible, and its effect on the soil matrix.

3. a description of the ice when in layers greater than 25 mm. The presence of soil inclusions and soil types is included.

Decomposed and disintegrated organic material is common surface soil in the north. High compressibility and moisture content limits its use for construction of the berm foundation unless special precautions are taken. Peat has been used as a construction material for impoundment structures but excessive deformation must be prevented.

Silt and clay comprise the fine-grained soils which feature reduced permeabilities and higher frost susceptibility than the coarse-grained soils. Liquid impoundments founded on fine-grained materials have reduced liquid losses but may suffer from thaw settlement as the material warms beneath the lagoon. Where permafrost is not present, such as in thaw windows, saturated fine-grained soils may experience considerable consolidation settlement.

Coarse-grained soils include sand and gravel which characteristically have a high permeability. Well graded, coarse-grained soils are readily compacted and form stable structures. Settlement and frost heave problems are not usually associated with foundations on these materials however, lagoons founded on, or constructed of, coarse-grained soil will require an impermeable membrane to prevent seepage and potential piping type failures of the embankment. Figure 5.3 summarizes the permeability ranges of some typical soils.

In the frozen state, each of the above materials may improve their engineering properties for lagoon construction. They generally have increased strength and reduced permeability. High

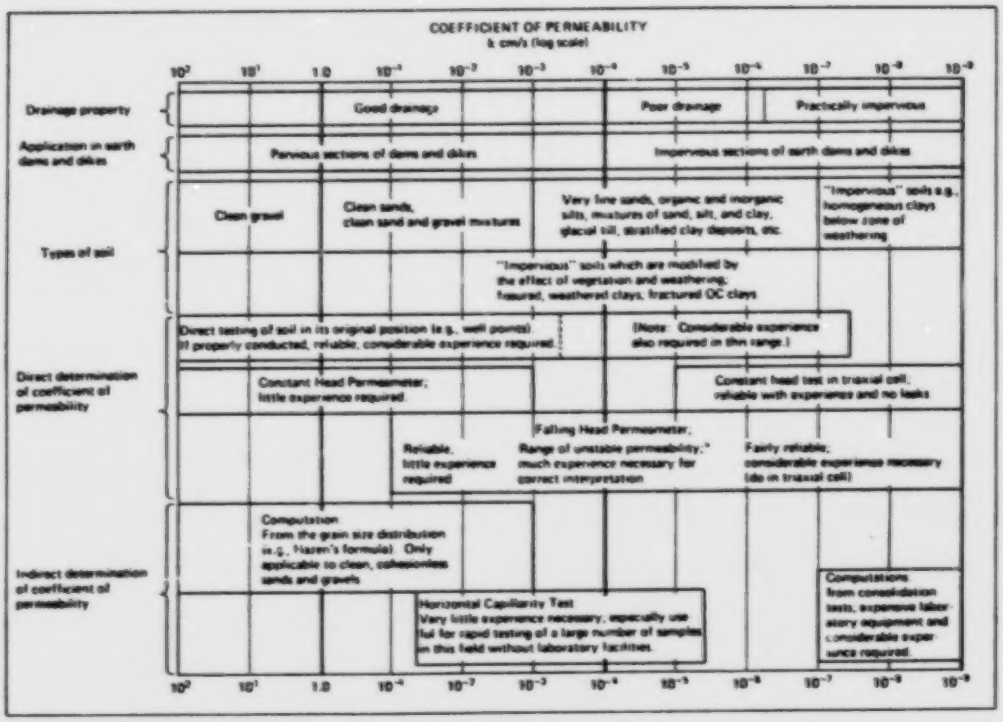
ice contents in the soil may produce large amounts of deformation under load.[200] These materials are normally not used in the frozen state since it is virtually impossible to prevent them from thawing. When thawed the frozen properties disappear creating potentially unstable conditions as the water content increases.[199, 200]

In most soils and at each location, it is a discontinuity or abrupt changes in soil type which are important at the site. It is important to identify these and have a qualified geotechnical engineer carry out all investigation related to site location, selecting design parameters, and the design of the earth structure.

5.3.1.3 Tests

Lefebvre *et al*[200] performed stage creep tests on block samples of peat, which included pore pressure and direct permeability measurements. The compressibility and permeability of peat were found to be important when evaluating the possibility of constructing berms on peat deposits. When the peat subgrade is thick and the amount of construction material limited, this may be an attractive method for construction.

Figure 5.3 - Soil Permeability Ranges
(from Casagrande[3''])


COEFFICIENT OF PERMEABILITY
k cm/s (log scale)
Drainage property
Good drainage
Poor drainage
Practically impervious
Application in earth dams and dikes
Pervious sections of dams and dikes
Impervious sections of earth dams and dikes
Types of soil
Clean gravel
Clean sands, clean sand and gravel mixtures
Very fine sands, organic and inorganic silts, mixtures of sand, silt, and clay, glacial till, stratified clay deposits, etc.
"Impervious" soils e.g., homogeneous clays below zone of weathering
"Impervious" soils which are modified by the effect of vegetation and weathering, fissured, weathered clays, fractured OC clays
Direct determination of coefficient of permeability
Direct testing of soil in its original position (e.g., well points) if properly conducted, reliable, considerable experience required.
(Note: Considerable experience also required in this range.)
Constant Head Permeameter; little experience required.
Constant head test in triaxial cell, reliable with experience and no leaks
Falling Head Permeameter;
Reliable, little experience required
Range of unstable permeability;* much experience necessary for correct interpretation
Fairly reliable; considerable experience necessary (do on triaxial cell)
Indirect determination of coefficient of permeability
Computation
From the grain size distribution (e.g., Hazen's formula) Only applicable to clean, cohesionless sands and gravels
Computations from consolidation tests, expensive laboratory equipment and considerable experience required.
Horizontal Capillarity Test
Very little experience necessary, especially useful for rapid testing of a large number of samples in the field without laboratory facilities.

*Due to migration of fines, channels, and air in voids.

Permeability, drainage, soil type, and methods to determine the coefficient of permeability

5.3.1.4 Construction Materials

Construction materials required at the site include soil suitable for berm construction or impervious material (clay) for lining the lagoon when coarse-grained soils predominate. Identification of the feasibility of cut and fill operations is necessary at an early stage in the design. Factors which affect this decision are the location of the water table, type of soil, thermal condition, and the proximity of borrow material. High water tables in coarse-grained or silty soils may require costly dewatering and present uplift problems with the lined structure. Generally, as the amount of permafrost increases, the design approach will be to maintain the existing permafrost surface as the lagoon base. The design depth of the proposed lagoon will be achieved by constructing berms to the required height. The possibility of dredging material for construction purposes should not be overlooked. It is suggested that the environmental impact of such activity would be less than excavation of borrow material on land in the long term.

5.3.2 Earth Structures

The standard reference, Design of Small Dams,[3'1'] provided detailed design approaches to earth and rock structures. Basic design criteria included:

1. the necessity for maintaining stable side slopes under all conditions of construction and operation, particularily

during periods of drawdown;

2. consideration of stresses imposed on the foundation by the lagoon embankments particularily if the thermal conditions are altered in ice-rich soils;

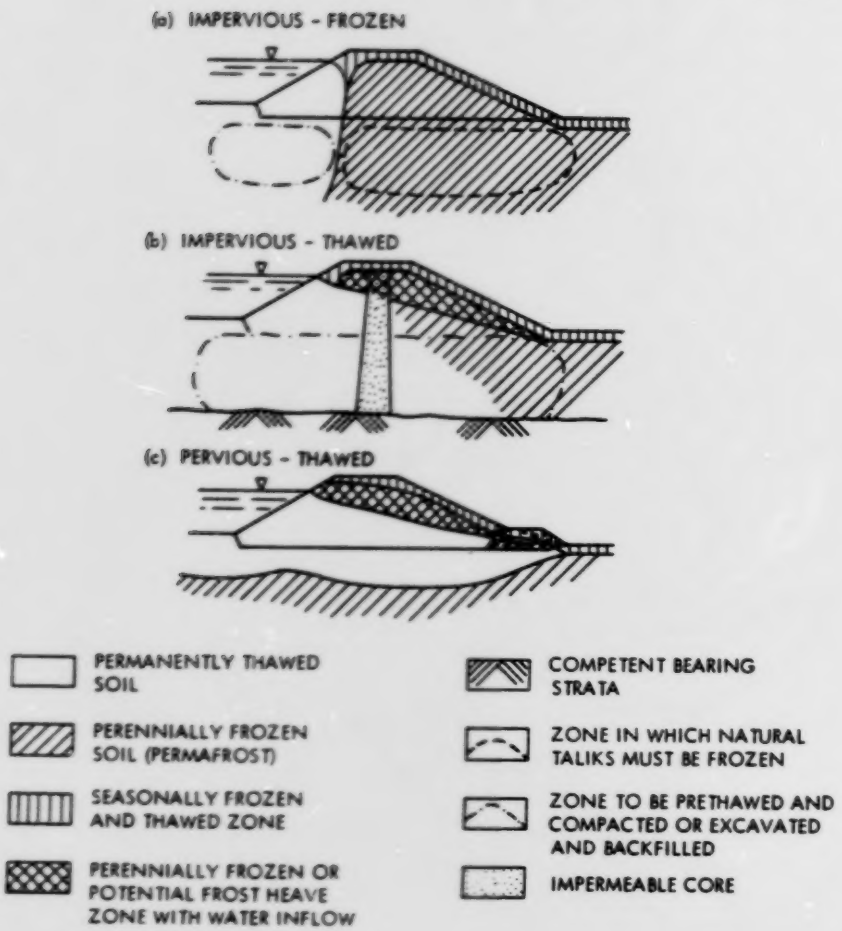
3. analysis of seepage flows through the embankment to eliminate possibly excessive neutral stresses from occuring and to predict possible hydraulic piping conditions which may cause structural failure; and

4. the lagoon embankment should be protected from overtopping and wave action.

5.3.2.1 Thermal Regime and Thaw Settlement

Designing embankments for lagoons in permafrost regions follow the same criteria as above but consideration of the impact of the lagoon on the ground temperature regime beneath the lagoon must be analysed during the design.[2,12] Typical thaw bulbs which form under water impounding earth structures are shown in Figure 5.4.

Figure 5.4 - Thermal Regimes of Berms on Permafrost (from Johnston[111])


(a) IMPERVIOUS - FROZEN
(b) IMPERVIOUS - THAWED
(c) PERVIOUS - THAWED
PERMANENTLY THAWED SOIL
PERENNIALLY FROZEN SOIL (PERMAFROST)
SEASONALLY FROZEN AND THAWED ZONE
PERENNIALLY FROZEN OR POTENTIAL FROST HEAVE ZONE WITH WATER INFLOW
COMPETENT BEARING STRATA
ZONE IN WHICH NATURAL TALIKS MUST BE FROZEN
ZONE TO BE PRETHAWED AND COMPACTED OR EXCAVATED AND BACKFILLED
IMPERMEABLE CORE

It is impractical to prevent lagoons from disturbing the ground thermal regime, therefore embankment design must account for thaw settlements. A knowledge of soil properties, soil and ice interfaces, and identification of ice-rich areas is necessary to predict thaw settlements. Earth structures can accommodate a certain amount of uniform settlement, however if liners are used or differential settlement occurs, failures of the structure are possible. The usual method of evaluating settlement is to apply a one dimensional thaw consolidation model modified from Terzaghi's Theory of Consolidation.[213] Embankments have been successfully built on frozen ground using frozen material.[214] [215] Johnston[215] reported foundation settlements of 1.8 metres were anticipated for the dykes at the Kelsey River generating station in northern Manitoba. The design accommodated the settlement and no special measures were taken to prevent thawing of the ice-rich foundation soils.

5.3.2.2 Phsyical Features and Stability Analysis

Seepage into the berm from the lagoon must be prevented. Therefore clay which is not frost susceptible is a desirable material. Peat can be placed to form the core of the berms since the core will be frozen, they would be fairly impervious and also have a lower thermal conductivity than other soils.[213]

Other soils are likely to be frost susceptible or pervious, therefore a liner must be designed. Design criteria for a liner includes:

1. membrane compatibility with the contained substance;

2. required service life;

3. seepage criteria;

4. possible membrane abrasion;

5. the difference between the support provided and the support required, which determines whether a supported or unsupported membrane is selected; and

6. climate; including wind direction and speed, and temperature.[214]

Examples of liner materials include concrete, asphalt, soil cement, spray-on sealants, compacted clay, clay admixtures, ice, and synthetics.[217] Asphalts and soil cements are subject to shrinkage cracks, tension cracks and inconsistent application. The high permeability which may result renders these liner systems unacceptable for wastewater lagoons.[218, 219] Acres[220] evaluated various sealant techniques and the stability of spray-on products when exposed to cold climatic conditions and found them unsuitable and their ability to withstand differential movement was low.[219] A thick layer of well compacted clay will provide a lining for the lagoon. Care must be taken not to let the liner dry as it may crack.[219] Irregularities within the compacted clay liner such as silt and sand seams, and fissures can affect the permeability.[221] One clay which has found use is bentonite which is known for its swelling characteristics when

mixed with water. At least 30 percent clay is required to effect a seal and reduce the permeability.[223] However, the swelling property of bentonite and its sealing ability is jeopardized when in contact with a liquid containing high cationic concentrations.[223] This may limit its use as a liner for lagoons.

A synthetic liner is believed to be the best alternative for lining a wastewater lagoon in the north. Synthetic liners are available with different chemical compositions, physical characteristics, compatibility with wastes, costs and methods of installation.[214] Consideration should be given to the following properties when selecting a synthetic liner:

1. mechanical properties;
2. overall weathering;
3. temperature characteristics;
4. overall field splicing; and
5. coefficient of permeability.

Failure of a liner is often due to poor design, or installation and operation, but seldom to the lining material.[217, 221]

The physical size the berm required to contain a sewage lagoon depends on:

1. the volume which was determined during process design which incorporates treatment requirements, plus sludge and ice volumes;

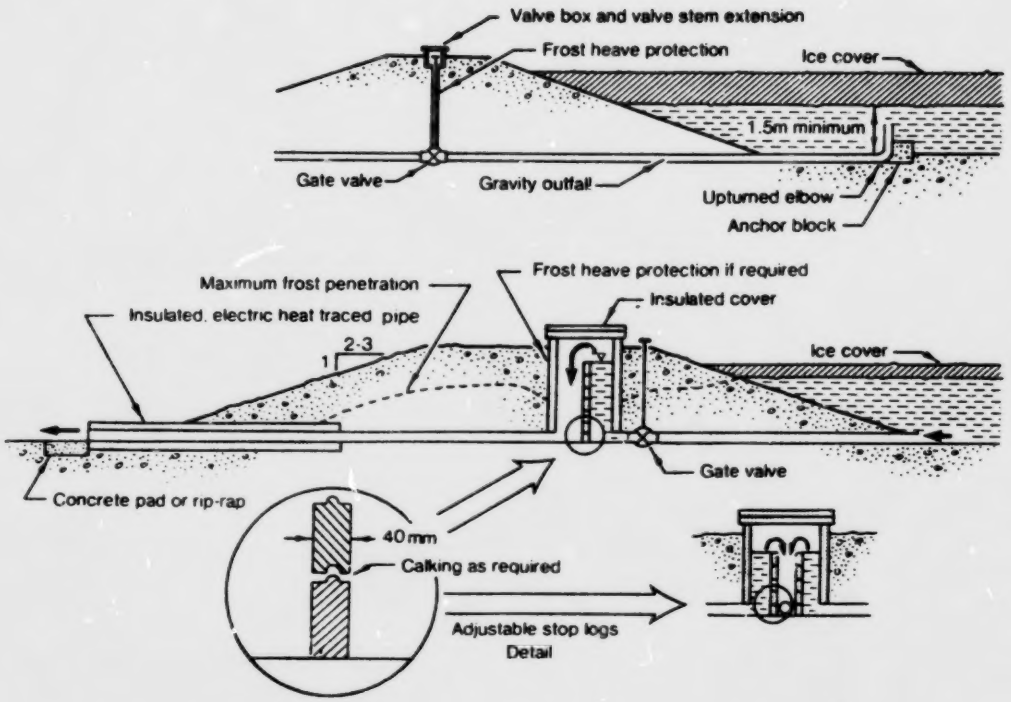
2. the available surface area and depth of the lagoon; and

3. the designed side slope.

Dawson[43] suggested that berms be as steep as possible to provide maximum volume in a minimum area. An opposite view was taken by Fielding[234] who found that berm erosion by wave action was severe at steep slopes and recommended 4:1 (horizontal:vertical) as maximum for clay soils. Flatter slopes will increase the shallow area of the lagoon resulting in more nuisance vegetation.[8] Side slopes between 3:1 and 6:1 on the inner slope were reported to limit potential damage from ice and waves. The exposed slopes of the berms should be capped with riprap or seeded to reduce erosional effects of the environment.[311] A typical cross-section of a lagoon facility is provided in Figure 5.5. The side slopes shown exceed those recommended above and should not be considered acceptable.

The simplified Bishop method or the Morgenstern and Price method can be used to determine the stability of the designed slopes. It is recommended that a check of the computer output be made with a hand calculation for each problem.[333]

Figure 5.5 - Typical Berm Cross-section
(from Smith *et al*[11])



5.3.3 Appurtenances

Appurtenances refer to anciliary devices which a lagoon depends upon to operate. These include sewer pipes, inlet and outlet structures, outfalls, and flow control devices. These must be incorporated into the design of the earth structure and included in the thermal analysis. Figure 5.5 illustrates various ancillary devices.

Thaw settlement zones can have a severe impact on conduits in and out of the lagoon particularily at the membrane interface. One alternative is to locate conduits over the berms rather than through them. This would eliminate sealing problems around the pipe and at the membrane and eliminate pipe settlement problems. Where thaw settlements are not anticipated, it may be possible to place pipes through or below the berms. Seepage along the pipe/soil interface must be minimized by the use of cut-off walls.

Outfall structures require special attention. For the design of a surface outfall, four critical time periods must be recognized:

1. fall freeze-up;
2. extremely low temperature periods in the winter;
3. spring break-up; and
4. high summer flow periods.

The type of receiving water body and the nature of the ice formed are also important.

In the fall, the formation of frazil ice due to the supercooling of the receiving water may result in blockage of the discharge line. During periods of very low temperature, both free fall and subsurface outfalls may be blocked off with ice and this must be accounted for in the design of the alternative chosen.''

A unique aspect of northern communities is that many have trucked waste collection systems, hauling both concentrated and moderately diluted wastes to lagoon disposal sites.'' Special facilities must be provided which are convenient to the user and these must be incorporated into the design of a lagoon.

Smith *et al*'' discussed some desirable features of the trucked waste disposal point and noted that access is important and should be available in all weather, with minimum grades on the approches. The access should be large enough to permit all types of vehicles ready entry.

5.4 CONSTRUCTION

Earthwork is one of the most critical activities concerning the engineer during cold weather.''' Holubec *et al*''' observed earthwork contracts were difficult to administer in permafrost regions due to the many unknowns. The greatest flexibility in construction may be obtained by using force accounts, however, this method may lead to large cost overruns if adequate

accounting and supervision are not provided. Unit price construction, with proper contract specifications and detailed design drawings, is usually the most economical approach.

The task of scheduling a construction project in the north is an important one. Information obtained during the site investigation concerning soil types, groundwater and equipment suitability will assist in the scheduling activity. The possibility of staging the construction over the summer and winter should be evaluated.

5.4.1 Foundation

5.4.1.1 Site Preparation

Organic material is a widespread surface material in the north. A lagoon site in an area with these deposits will result in one of the following three choices:

1. remove all peat which may be a very costly decision unless the deposit is thin;
2. consolidate peat beneath the berm fill resulting in settlement for a long period after construction has finished; and
3. float fill on peat surface where the fill is thin.

The decision to remove peat from a site in a cold climate region should not be made hastily. Many people are of the impression

that peats are "weaker" than soft clays, due to their greater compressibility. However, peats are able to gain strength with compression and enhance their ability to withstand shear forces.[227]

Removal of overburden in continuous permafrost zones, will lead to the rapid degradation of the soil thermal regime and massive flows of water and soil may occur, reducing the site to a quagmire. The Inuvik lagoon was constructed without clearing or grubbing, and operating problems were encountered.[40] If possible, the surface deposits should remain undisturbed in warm, ice-rich permafrost soils.

5.4.1.2 Subgrade Preparation and Excavation

Kays[228] recommended that the berm subgrade be compacted to 95 percent of Standard Proctor density to provide a uniform crust on which to carry out fill placement. Where permafrost exists, fill should be placed early in the spring before the active layer has had time to develop. This is to slow the development of a thermokarst situation beneath the berms and within the lagoon and will also provide a solid base on which to compact the fill.[211]

Excavation of various soils is determined by the soil type, thermal condition, water or ice content, and the type of equipment available. Normal methods of earth moving may be used provided conditions are suitable.

As the temperature decreases, the difficulty of excavating all saturated soils increases. Homogeneous frozen soils are more difficult to excavate as the density increases. Soil stratification aids excavating some soils. The lower moisture content of the layers of sand within silt and clay layers provide weak planes for ripping.[22] Since sand and gravels often have lower moisture contents than silts and clays, they are usually easy to excavate. Detailed studies have been carried out by the U.S. Army Cold Regions Research and Engineering Laboratories (CRREL) into the excavation of coarse as well as fine-grained soils. Moore and Sayles[22] provided a summary of this work plus a detailed bibliography.

Organic soils are difficult to excavate due to their high moisture content and degree of saturation. Although the organic mat provides support for equipment when frozen, the excavation of frozen peat is very difficult. Ripping the peat before using scrapers may increase the rate of progress.[22]

If frozen soils are excavated, controlled blasting may be implemented. Proper design of charges and their placement will allow accurate excavations to be made. Small charges will break the frozen material into pieces which can be easily excavated.[24]

Final grading of the lagoon excavation must provide for drainage to a low point and present smooth contours.[40]

5.4.2 Embankment Construction

A berm is an engineered fill, therefore attention must be given to compaction quality control. Many factors affect soil compaction. Some of these are grain-size, moisture content, temperature, and compactive effort.

Coarse-grained soils can be placed when frozen, provided the moisture content is low, since there will be little thaw settlement. If the soil matrix is saturated difficulties in compaction may occur, even supposing the material could be excavated.

It is difficult to use frozen silt and clay for winter construction since these usually contain excessive frozen water, which results in large settlements and instability when thawed. One method of avoiding this problem is to stockpile frozen material during the summer where it can thaw and drain.

The construction of berms is difficult with frozen material since it is difficult to compact. The resulting low density is believed to result in excessive settlement and loss of stability after the soil thaws.[22] If high quality compaction of berms is required, the material must be placed and compacted in an unfrozen state during the summer.[21]

The construction methods used to build berms in northern regions during the summer are similar to methods used in the south. The fill material will need exposure to warm air to promote melting of ice prior to placing in the fill section.[19]

Conventional compaction equipment may be used and compactive effort may be higher to obtain suitable densities at the over optimum moisture contents likely to occur. The use of silty soils should be avoided since they have a very narrow density range at optimum moisture content.

5.4.3 Liner Construction

The minimum temperature at which the liner may be installed is given by the manufacturer. This limits the opportunity to install many types of synthetic liners during the winter. Supervision of the work should be provided by the supplier of the liner.[204]

A protective layer must be placed on the subgrade for two reasons. This will protect the liner from puncturing and tearing by material in the subgrade. Melting of the soil will be retarded if the protective layer between the heat source and the frozen ground has insulative characteristics.[40]

An underlay of polyurethane blankets (foamed onto sacking) beneath the liner may provide the required thermal insulation and form a protective bedding for the membrane. Sawdust may also be used as a bedding material or protection from overburden.[230] The rolls of lining should be oriented around the site so that when unrolled they will be properly positioned. Orientation markings should be printed on the liner as well as the wrapper.[211]

To reduce brittleness the folded liner may be heated using forced air heaters before being placed.[233] The liner should be placed in low winds and ballasted with sand bags until anchored in place. The seams should be perpendicular to the toe of the slope so that any strains will not pull these apart.[211, 213] Liners should be anchored on top of the berms so that they do not blow away or pull off the side slopes.[233] The membrane should be placed in a trench dug on top of the berm backfilled and compacted to hold it in place.[204] Care must be taken during installation that workmen do no damage and equipment is not allowed to ride on the membrane except under the conditions recommended by the manufacturer.

A compacted soil cover should be placed over the liner. This protects the liner from effects of infrared and ultraviolet light. The cover may act as a ballast if water collects beneath the liner. The cover will also provide protection from ice and surface waves. Kays[228] suggested a minimum lift thickness of 150 mm, whereas Matrecon[211] recommended 460 mm. The wave action may cause cyclic increase in pore pressures in the soil cover resulting in sloughing of the side slopes. Low side slopes and good compaction will help to maintain a soil layer on the berms. Flat side slopes allow the ice sheet to ride up the slope without damaging the liner.

Failure by differential settlement need not occur if good site investigation practice and design are utilized. Flexible and thicker membranes can tolerate more differential settlement

without damage. The liner should be installed with 5% overlap in order to accommodate differential settlement of the subgrade.[3'']

Allen, Vinson and Bell[23'] concluded in their research that in a dry, distilled or saline water environment freeze/thaw cycling has no appreciable influence on the load-strain-strength characteristics of geotextiles. A decreased rate of creep for polypropylene geotextiles is associated with a reduction in temperature. Their experiments also showed that subfreezing temperatures do not adversely affect the load-strain-strength and creep characteristics of the material.[23']

Local depressions and soft spots may exist on the subgrade. The placement of a geotextile over the subgrade may act to bridge over these areas and thereby improve the performance of the total berm.[23]

5.4.4 Structures and Appurtenances

The construction of conduits, manholes, and outfalls has been adequately covered for general applications in the "Cold Climate Utilities Delivery Design Manual".[1''] Special applications to the structures found in a sewage lagoon was covered briefly in the Design Manual. Thaw settlement and the interface between the liners and pipes or structures are of concern, but have not been investigated in depth. Foundation preparation and trench backfill follow the same guidelines as in the foregoing sections.

5.5 CRITIQUE

The selection of a location for a lagoon in cold climates is dependent upon access to the community and air movement, but primarily it is governed by soil conditions. Detailed knowledge of the subsurface soil conditions is required especially if permafrost is present. Lack of information may result in untimely failures due to uncontrolled thaw resulting from damaged ground thermal regimes.

The assessment of the soil conditions must be carried out by qualified permafrost specialists to ensure that the worst site conditions for the design and construction of the lagoon are obtained. This will allow for proper and economical design of the embankment. Site conditions will determine the type of liner and its design for seepage control.

It is important that the initial thermal conditions be completely understood and the response of the soil thermal regime to the facility over time be determined.

The construction of berms for lagoons in cold regions is dominated by the presence or absence of permafrost. Unfrozen ground conditions utilize conventional construction techniques used in southern areas for small dams. Special attention must be paid to foundation soils since these will determine if a liner is required. Construction of liners requires special attention to quality control since leaks due to construction method can have serious ramifications on slope stability from ice lense formation

and piping.

When frozen ground conditions are present, gradual thaw of the underlying soils must be anticipated. Therefore the berms and liners must accommodate any settlements which occur. Synthetic membrane liners are most commonly used since they are durable, provide some insulation capacity, and can adapt to large settlements.

In both the permafrost and non-permafrost regions, summer construction and the use of unfrozen soil will allow a well compacted berm and liner to be constructed. Cold weather compaction and the use of frozen material results in poor densities and unstable berms. These methods may be forced upon the designer due to access problems and/or length of construction season.

6. OPERATION AND MAINTENANCE CONSIDERATIONS

6.1 INTRODUCTION

The lagoon can be designed perfectly yet will fail to meet design objectives if not operated and maintained properly. In fact, marginal lagoons can produce good quality effluent if operated in a diligent fashion.[233] [234]

A recent joint publication by the Water Pollution Control Federation and Environment Canada, entitled WPCF Wastewater Treatment Skill Training Package: Wastewater Stabilization Ponds,[233] is an excellent training package aimed at the operators of municipal treatment facilities. Major contributors to the document were Zickefoose and Hayes[158] and Karn.[234]

6.2 PERSONNEL

Since lagoons are used extensively in small towns, it is not uncommon that the public works departments are quite small, consisting of one or two permanent employees.

The need for training may not seem important but to have a system which fulfills the designer's goals and the taxpayer's expectations, there must be a semi-skilled operator to maintain and operate a lagoon system.

This role is usually neglected but there are training materials available. The best is the WPCF publication mentioned

above which is a self-teaching manual on the most important aspects of the lagoon system. Its availability and usefulness needs to be publicized by provincial and territorial regulatory agencies.

6.3 OPERATION

The operation of a lagoon involves flow regime control and performance monitoring. In some cases, the collection system is an integral part of the lagoon operation such as in trucked collection of undiluted and moderately diluted wastes.[13]

6.3.1 Configuration

Configuration applies only to multi-celled lagoon systems where valving and piping allow a choice of series, parallel or combined use of the cells. Gloyna[1] and Smith *et al*[18] illustrated some typical arrangements.

Series operation consists of one cell flowing into another and is the desirable mode of operation when possible since higher quality effluent is obtained.[33,34] Permanent piping and valves allow control of this system. Operational requirements are minimal.

Ponds simultaneously loaded are usually in parallel and have flow distributed by a splitter manhole or distribution chamber. This arrangement is useful during low dissolved oxygen conditions when it is desirable to reduce the loading such as in winter.[18]

Again, piping and valves are located to allow control of the system and operating requirements are few.

Optimum efficiency may be obtained operating the system as a combination of parallel and series cells. The operator would be required to adjust the flow control devices until a satisfactory effluent is produced.

6.3.2 Discharge Procedures

Discharge can be continuous, intermittent, or non-existent. The later two terms are also known as controlled and total retention, respectively.

Continuously discharged efffluent was the traditional discharge mode but its use in Canada is becoming increasingly rare, even on large receiving waters where there is some concern about pathogen survival.[4] Alberta Environment[33] investigated a seasonal type of continuous discharge system. The system involved three or four short to intermediate retention cells feeding a long retention (120 to 210 days) storage cell. This cell filled over the winter, and then was released gradually during the summer months. Very high degrees of treatment were obtained. The only drawback to this method was the requirement for a watercourse with adequate year round flow.

The major advantages of continuous discharge are smaller land requirements and less operating attention.

Controlled discharge lagoons have a storage requirement of 180 or 365 days depending on regulations and receiving water protection requirements. Karn[43] emphasized that only enough wastewater to provide the next storage volume should be discharged since the effluent will benefit from maximum retention times.

The choice of autumn discharge is preferable to spring since receiving waters are generally adequate and the quality of the effluent is high, particularily after the first cold spell reduces algae.[44]

Middlebrooks *et al*[47] stressed the need for choosing the correct time and rate of discharge to protect receiving waters. They outlined the usual procedure for seasonal discharges as did the EPA design manual.[144]

Sometimes chemical coagulation by aluminum or ferric salts is used prior to discharge to remove colloidal material and phosphorus.[118, 238] The use of a motor boat and chemical is all that is required.

This method requires more operator attention than the previously discussed approaches. It also requires a higher degree of operator training to take advantage of the full potential of this type of operation.

Total retention relies upon seepage and evaporation to maintain a liquid balance in the lagoon.[47] No operator attention is required for this type of discharge.

6.3.3 Monitoring

Monitoring lagoon performance is a duty of the operator, particularily prior to discharge of lagoon effluent.[4] The operator should take samples routinely and send them to a laboratory for analysis.[3,5]

Records should be kept of raw wastewater characteristics, flow rates and effluent characteristics. Sludge accumulation rates should be determined through annual measurements of sludge depths in lagoons. In addition, information on snow and ice cover, weather conditions, lagoon and wastewater temperature would be of use. Unfortunately, in remote, isolated communities, it is not practical to have routine sampling and testing done for reasons of cost and the travel time to a laboratory.

6.3.4 Access Points

Smith *et al*[5] discussed some aspects of disposal points at lagoons including:

1. a heated building with "drive through" access;
2. parking facilities for collection vehicles when not in use;
3. splash pads and/or revetments to prevent erosion of the lagoon bank;
4. cleaning equipment to maintain sanitary conditons; and
5. provisions for non-biodegradable, plastic "honey bags" which

cannot be disposed of in the lagoon.

Facilities must be kept clean and the area free of dangerous ice and snow conditions so that the facilities will be used, otherwise unsanitary conditions will occur around the community.

6.4 MAINTENANCE

6.4.1 General

Routine inspection and maintenance of appurtanences is a requirement for trouble free operation. Valves, control manholes, fences, and outfall structures are often neglected until the time comes for use, resulting in costly delays.

There is little relevant literature on this topic in northern communities.

6.4.2 Vegetation

Vegetation contributes to three serious problems; (i) blocking the wind, preventing mixing, (ii) providing habitat for nuisance insects, both in the water and along the berms and (iii) clogging the pond preventing mixing and limiting light penetration.[1,4,23]

Trees adjacent to ponds should be cut and grass mowed regularily. Aquatic weeds should be discouraged by maintaining water depths greater than 1.0 metre.[23]

6.4.3 Insects

Mosquitoes are the most frequently found nuisance insect but only ponds with poorly maintained vegetation have had a significant problem.[1, 51, 240] Fair *et al*[48] reported that *Culex tarsalis* (the vector of equine encephalitis) favoured lagoons due to algal CO_2.

6.4.4 Odours

Most odour problems are of short duration in the spring unless a lagoon system is severely overloaded or materials such as dairy wastes are being treated.[173, 239]

Treatment for odour problems has included parallel operation of ponds, treatment with $NaNO_3$, supplementary aeration and recirculation of oxygen rich effluent.[188]

Gloyna[1] noted that occasionally Cyanobacteria (blue-green algae) formed large surface mats creating anaerobic conditions in the water column which in turn produced odours. He recommended mechanical or physical removal under those conditions to eliminate the odour.

6.4.5 Erosion

Erosion is caused by wind action and has been found to be severe for slopes less than 4:1.[241, 243]

Fielding[2,3,4] conducted field and laboratory trials considering wind reach, wave height, and soil grain size and concluded grain size and slope were the most important factors. For clay materials, a 4:1 (horizontal:vertical) minimum slope was recommended with rip-rap at the waterline if necessary. He also pointed out that seasonal variation in water level could lead to very expensive erosion control. Therefore slopes should be considered carefully.

All authors agreed that shallow-rooted, dense grass cover is a necessity to prevent erosion of the banks, but suitable grasses for use in the arctic have not been mentioned. Deep-rooted grasses should be avoided as these can damage the impermeable liner and cause root channels in the clay embankment.

6.4.6 Snow and Ice

As seen in Section 3, snow greatly impacts light penetration, thereby eliminating photosynthetic oxygen production.

Snow control probably is not important in the far north since the light in the winter is negligible. In fact, the opposite may be desirable, since snow provides insulation and may reduce the ice thickness if it accumulates on the lagoon.

6.4.7 Sludge

Schneiter[213] found there was little information on sludge removal in cold climate lagoons. The usual practice is to drain a lagoon and use earth moving equipment to remove sludge.[213] Others[214] have used suction dredges to clean lagoons.

Dawson and Grainage[183] proposed having a fallow cell in a three cell system which would be cleaned as required.

6.4.8 Animals

Burrowing animals such as gophers and muskrats can cause serious leakage problems, damage impermable membranes, and even lead to failures of the embankment. They should be discouraged from living adjacent to or in a lagoon.[211]

Muskrats can be trapped or water levels changed often enough to send the muskrat looking for a more favourable environment.[183] Gophers are usually exterminated.

6.4.9 Equipment

Karn[216] provided a list of the basic equipment requirements for a lagoon operator including lawn mowers, valve keys, and appropriate hand tools. Depending on the size of the facility, the equipment requirements can be quite modest.

6.5 SAFETY

The Skills Training Package[333] by the WPCF and Environment Canada provided a good summary of the usual safety requirements particularily with respect to the dangers of sewer gases and operation of light equipment such as tractors.

In addition, public safety and vandalism were covered adequately.

6.6 CRITIQUE

6.6.1 Personnel

Training is the key element with personnel. Lagoons require moderately skilled operators since an understanding of discharge techniques, alum dosing, and mechanical maintenance will ensure a consistently high quality effluent.

A problem found in developing countries and applies equally in northern Canada, is a poor understanding of the importance of maintenance. Facilities designed by people of one culture may not operate as planned when used by people of a different cultural background.

Appropriate training of operators in the North should reduce this type of problem. The existing literature does not atttempt to analyse this problem.

6.6.2 Operation

The most important operations in a lagoon are effluent discharge, coagulant addition (if practiced), and disinfection (if practiced).

It may be economically feasible to have one highly trained regional operator who would be responsible for the operation and maintenance supervision for a number of small communities.

Operation of serial lagoons seems the most attractive approach as discussed in Section 4. Each lagoon system should be assigned an operating schedule enabling the regional operator to plan the optimum operation of the lagoons under his jurisdiction and to coincide with the best times to discharge to the receiving environment.

Controlled discharge facilities are being used more frequently. There is a little information available and it would be useful to conduct interviews with each provincial authority to determine configurations and discharge procedures currently used.

6.6.3 Maintenance

Short growing seasons in the North hamper the establishment of ground cover on the embankments and provision for interim slope stabilization should be made. This point has not been addressed by engineers and input from landscape architects or botanists should be sought.

Nuisance insects are a second source of concern. Reports on mosquito breeding originate in regions where the problem is not as intense as in the North. Studies on breeding in northern lagoons have not been done, however the mechanisms which prevent mosquito breeding in southern regions (wave action, vegetation control) probably apply in the North. Therefore maintenance programs should be directed towards vegetation control in the vicinity of the lagoon.

Little attention has been given to discharge points in truck and self haul collection systems. Difficult access is a disincentive to proper utilization of the system and may contribute to community health problems. The use of non-degrading honey bags complicate the issue. Development of appropiate bags would be advantagous.

6.6.4 Monitoring

Routine monitoring of performance is not carried out in northern facilities, usually due to the difficult logistics of sampling, transporting, and costs. It is desirable to have a recording system in place for lagoon performance and sludge accumulation so that future designs are efficient and economical.

7. UPGRADING LAGOON EFFLUENTS

7.1 INTRODUCTION

Two conditions result in the need to upgrade lagoons:

1. more stringent government requirements; and
2. overloaded facilities.

Various alternatives have been proposed and used to upgrade lagoon effluents which Middlebrooks *et al*[7] summarized as:

1. land application by;
    - slow rate infiltration;
    - overland flow;
    - rapid infiltration; or
    - wetlands disposal.
2. filtration methods such as;
    - intermittent sand filters;
    - rapid sand filters;
    - rock filters; or
    - microscreening.
3. dissolved air flotation;

4. chemical treatment;

5. mechanically aided systems;

6. aquaculture; and

7. facility and operational modifications.

Several U.S. EPA publications dealt with sundry upgrading options for lagoons.[138 248 244 247 248 249 250] Many of the reported techniques dealt with suspended biological solids removal. Algae comprised the bulk of these solids, which may contribute to unacceptable BOD and nutrient loads on the receiving environment, particularily when natural dissolved oxygen levels are low.[251]

The presence of large numbers of indicator organisms suggest pathogeni: bacteria and viruses may also be present.[252] Studies of bacterial removal kinetics indicated the die-off rate had a strong temperature dependence, with extended survival times, which has led to the practice of disinfecting cold climate lagoon effluents as an upgrading stratagem.[100]

Nutrients contribute to eutrophication of natural waters. Existing low background levels, cause the impact of concentrated waste nutrients to be greater in northern rivers and lakes. Phosphorus and nitrogen removal may be necessary as an upgrading step for some lagoon effluents.[119 253]

In northern lagoon applications, only chemical precipitation, land treatment, and auxiliary aeration have currently been investigated as upgrading methods.[104 163 254 255]

7.2 LAND APPLICATION

A recent U. S. EPA report[254] provided a comprehensive discussion on all aspects of land treatment of municipal wastewater, including planning, theory, design, and operation. Middlebrooks *et al*[47] reviewed applications to lagoon effluent upgrading and stated that regions with severe winters may require winter storage. This may not necessarily be true as will be discussed.

7.2.1 Slow Rate Infiltration

Slow rate land applications have been studied by many researchers.[257, 258, 259, 260] Purification relies on soil microorganisms and a cover crop of plants to remove organic matter and nutrients. These processes are inhibited or halted by snow and cold temperatures. The presence of fine grained, occasionally ice rich, soils with low permeability, cold ground temperatures, and a short growing season has limited the use of this method in the north.

7.2.2 Overland Flow

This is essentially the same as slow rate infiltration with the exception that it occurs on a slope. The same disadvantages apply to this method. Ehlert[261] reported good performance from this method in southern Ontario.

7.2.3 Rapid Infiltration

Rapid infiltration has the most potential for northern applications.[203, 242, 243] The advantages of this system include an infiltration basin containing a large volume of water which conserves heat, bacteria play a reduced role, and vegetation is not a requirement to obtain treatment. Disadvantages may include freezing of the soil during cold periods, reliance on suitable soil conditions for permeability and thawed stability, and potential groundwater pollution.[4]

Sletten[203] noted that Alaskan rapid infiltration basins operated during the summer months established a soil heat regime which reduced frost penetration in the winter. This was enhanced by snow and ice accumulation. The EPA manual[254] suggested some infiltration system modifications for use in cold regions. These were:

1. mowing grassy or weedy areas followed by disking prior to freeze-up. This prevents grass and soil freezing the ice cover to the ground.

2. digging a ridge and furrow system in the basin surface which helps create an ice bridge and prevents the "lid" from sticking to the ground; and

3. using snow fences to promote drifting over the basin which improves the heat retention capacity of the water and soil.

Nitrogen removal is accomplished by biological nitrification-denitrification in the soil.[4] Performance of 50 percent removal has been reported in temperate regions, with higher removals if denitrification conditions are optimized.[266] Cold environments inhibit the process kinetics.[4,5] The potential exists for high levels of ammonia and nitrate to enter ground or surface water posing a serious water pollution problem.

Phosphorus removals may range from 70 to 99 percent depending on the chemical and physical character of the soil.[266] Clogging of the soil matrix is a potential long term problem.

Microorganisms are removed by filtration in the soil and by adsorption to soil particles. Removals have been high.[266]

7.2.4 Wetlands

Wetlands are defined as areas where the water table is at or near the surface on a regular basis and which encourage the growth of hydrophytes.[264]

Nichols[265] reviewed the dynamics of nutrient removal in wetlands. He stated that removals of phosphorus and nitrogen can be very high, and at low cost. Hartland-Rowe and Wright,[264] Slupsky and Firth,[34] and Shaw[267] studied the Hay River, NWT wetland disposal system. Hartland-Rowe and Wright recommended the use of *Carex* as a wetland plant, and at least 10 km of travel distance be present to achieve adequate reductions of microorganisms and BOD. Black *et al*[268] studied the feasibility of

using artificial wetlands to upgrade effluent from an Ontario lagoon. They reported results suggesting that artificial marshes were feasible in treating lagoon effluents concluding that retention time, configuration, flow rate, and temperature were the most important parameters. Poor winter performance was reported.

Effluent quality data is site-specific but the literature suggests that high BOD_5 removals using secondary effluent are attainable (70 to 90 percent) as well as high nitrogen removals (40 to 60 percent). However, design criteria are not currently available and this is an area which more research is required.

Peatland is another alternative disposal area. Labonte *et al*[269] and Dubuc *et al*[270] have reported encouraging results on the disposal of raw wastewater on peatlands in northern Quebec. Metcalf and Eddy[4] reported that high removals of phosphorus, nitrogen, and fecal coliforms were obtained in a Minnesota peatland investigation.

7.3 FILTRATION

7.3.1 Sand and Rock Filtration

Sand filtration has been shown to have the potential of achieving very good SS and BOD levels (5 mg/l).[271] Process efficiency is largely a function of algal growth on the filter surface. Intermittent sand filtration has been shown to be a

viable tertiary treatment device in warm climates.[247, 248]

Reynolds *et al*[120] reviewed three case studies in California, New Mexico, and Georgia on the use of sand filtration. An historical perspective and review of intermittent sand filtration of wastewater was compiled by Hill[272] and Harris.[273] Frozen filters and subsequent short circuiting was considered by Harris for filters operated in cold climates.

Three types of suspended solids removal systems were investigated in southern Ontario by Rupke and Chisholm.[274] These were chemical coagulation and sedimentation followed by filtration, air flotation, and microstraining. Mixed media filtration with anthracite and sand in a 0.2 m^2 filter bed having a nominal feed rate of 14.7 m/hr was found to be the most effective. The microstrainer used a 23 μm stainless steel cloth. No winter testing was conducted.

7.3.2 Microscreening

Wittman[275] conducted extensive field testing with a 1 μm polyester fabric for algal removal and found microscreening to be a viable process free of earlier problems with a corrodable 23 μm stainless steel cloth.[276]

Microscreening effectiveness may be independent of pH or the volumes of algae present.[132, 277] Life expectancy of a plastic 20 μm screen was reported by Koopman *et al*[278] to be two years or greater.

Shifts in algal community composition have been shown to be quite dramatic[277] as a result of filtration. Metcalf & Eddy[4] suggested that effective treatment could be attained when microscreening is coupled with sand filtration.

7.4 DISSOLVED AIR FLOTATION

This process is relatively expensive,[244] requiring addition of coagulants for successful algae removal. It also increases the bulk of the sludge to be removed and dewatered. Metcalf and Eddy[4] stated that typical doses of alum required for 70 to 90 percent removal of SS ranged from 50 to 200 mg/L, and although the chemical dosage was closely related to SS separation by flocculation and flotation, the characteristics of the wastewater were of importance. Middlebrooks *et al*[244] commented on the lack of data necessary for comparison of dosages of chemicals required for coagulation with dissolved air flotation but indicated nevertheless that considerably smaller dosages are required.

A flotation cell used by Rupke and Chisholm[274] was found to be incapable of producing high quality effluent consistently.

7.5 CHEMICAL TREATMENT

7.5.1 Coagulation and Flocculation

Several researchers[111, 284, 289] have studied the effectiveness of alum under various temperatures and in different

modes. Some findings of interest were:

1. the addition of alum to influent sewage followed by a precipitation unit before the lagoon proved most effective;[111]

2. best results were obtained during periods of ice cover;[111]

3. a 2.5 fold increase in BOD removal with alum addition;[284] and

4. high phosphorus removal was acheived.[111, 284, 286]

In-situ lagoon precipitation of phosphorus has been studied in cold climates.[118, 119, 283, 281, 282, 283] It was noted that the choice of chemical for a particular installation depended on factors such as the delivered cost, the quantity of chemical required, the ease of handling, storing and application, percent removal desired, and the amount and type of sludge produced.[283]

Graham and Hunsinger[118] found that alum was most cost effective in comparison with lime and ferric chloride ($FeCl_3$) and that it did not seem to retard biological activity. Also it was found easy to handle in liquid form.

Pollutech Pollution Advisory Services Ltd.[281] found 200 mg/L alum to be optimal in reducing phosphorus in lagoons to below 1 mg/L. Higher temperatures increased phosphorus in the effluent. This agreed with the work of Al-Layla and Middlebrooks[112] which indicated that when alum was used, algal cell coagulation

decreased as temperatures rose. Resolubilization of phosphorus was found to be minimal and could be controlled by additional alum dosage. Low dissolved oxygen concentrations also influenced resolubilization. Severe wind conditions hampered good suspended solids free effluent. Most researchers using $FeCl_3$ found good removals but the chemical was difficult to handle and the cost was high.[118, 281]

Work done with lime indicated several difficulties.[118, 281, 284] Lime required higher dosages than either $FeCl_3$ or alum and costs more. It required more manpower, produced more sludge, allowed substantial releases of phosphates, BOD, and SS after treatment and required additional equipment for preparation and dispersion. Also it was found that extremely cold temperatures required heavier doses to effect the same removal.

Another approach has been suggested by Freidman[277] which attempted to exploit the enhanced flocculatory nature of algae at the cyclical high pH values associated with their own activity. Sweep floc produced by $Mg(OH)_2$ precipitation at the high pH was most effective in removing the algal cells. In the late afternoon when the pH was highest the contents of the lagoon could be drawn into a seperate pond and then the $Mg(OH)_2$ could be added. A minimun dosage of 10 mg/L $Mg(OH)_2$ was suggested.

7.5.2 Disinfection

Concern about biological contamination of surface water has increased the use of disinfection as a unit process.

Various arguments for and against disinfection were presented by Smith and Bell.[206] They noted that controversy has surrounded the use of chlorine in terms of the public health benefits of reduced microbial populations,[204] as well as the question of toxicity to aquatic forms of life, and more recently, the impact of carcinogenic halogenated organics.[204, 207, 208] Chambers[209] pointed out the complexity of wastewater disinfection using chlorine compared with water treatment. Only well operated and maintained plants could perform chlorination adequately.

IEC[160] presented an impact matrix that associated the impact of disinfection alternatives on biological, socio-economic, and physical-chemical aspects. Disinfection with lime and chlorine exerted the most pronounced effects. Chlorination-dechlorination treatment indicated a lesser impact.

Some of the problems of cold climate disinfection of wastewater were addressed by Chambers.[209] He was critical that most research for cold water applications had been done on synthetic test waters.

The cost of transportating materials and associated energy use has not been addressed when considering disinfection for cold climate lagoons.

7.5.2.1 Chlorine

Johnson[211] reviewed the considerations of chlorinated lagoon effluents. Chambers[209] presented data comparing the effect of

hypochlorous acid on *E. coli* and three types of viruses, and noted that the virucidal effect of chloramines was very low. Culp[212] demonstrated chlorine inactivated some viruses at a faster rate than chloramine formation. Durham and Wolf[213] demonstrated that viruses were not necessarily affected by chlorine in the same way as coliforms. They also found that coliphages were more resistant to chlorine disinfection than coliforms.

The problem of treating lagoon effluents with chlorine is the destruction of algal cells resulting in a higher BOD_5 in the effluent, but the ultimate standard BOD will remain unchanged.[214, 215, 216] Others attempted to reduce the effects by using chlorine dosages not toxic to algae but effective against coliforms. While meeting with some success, controlling the dose was difficult.[214, 217] Other factors such as chlorine resistant microorganisms not represented adequately by coliforms, makes this an unattractive method.[48]

Johnson[218] noted that for lagoon effluents at cold temperatures, the reduction in the rate of chlorine disinfection was partially offset by reductions in the exertion of chlorine demand, but that the net effect was reduction in the chlorine residual necessary to achieve adequate disinfection.

Recently, the Ontario Ministry of the Environment studied chlorination of six lagoon effluents used for spray irrigation. A 4 mg/L chlorine dose and 10 minute contact time were used on the effluent in laboratory tests. Although much variability was

observed, it was concluded that a 4 mg/L dose and 10 minute contact time could reduce the total and fecal coliform densities to acceptable levels (to meet Ontario water quality standards). However, it was implied that because of the initial highly variable bacteria densities, overdosing might have been necessary. It was felt that a high algae concentration in the lagoon effluent was instrumental in preventing high bacterial reductions. Temperature was not considered as a variable. Insufficient data were collected to delineate mathematical relationships between the measured chlorine residual and the various effluent quality parameters evaluated. The viability of actually dosing the lagoon contents was not discussed.

Another problem with chlorine disinfection is the potential toxic effect on receiving water biota.[3,9] Gordon and Davenport[3,9] and Chambers[3,9] suggested that because chlorine persists longer at low temperatures, this might have a synergistic effect on oxygen starved biota at naturally occurring low dissolved oxygen levels in northern waters. Dechlorination with SO_2 gas or other reducing agents may be necessary.

On the basis of existing data International Environmental Consultants (IEC)[3,9] concluded that chlorination-dechlorination was the most cost effective, environmentally acceptable disinfectant for lagoon effluents.

7.5.2.2 Lime

Lime is an effective disinfectant at high pH and practical contact times.[39]

Some advantages of using lime are its relative insensitivity to low temperatures, insensitivity to organic concentrations, and a 30 minute contact time at pH 11.5 to pH 12 will provide effective disinfection.

The use of excess lime disinfection at low temperatures has been investigated by Morrison and Martin[38] and Schneiter.[3] Morrison and Martin found temperature was less important than pH, where disinfecting ability was concerned. Morrison *et al*[39] stated that an average lime dosage of 430 to 1000 mg/L was required for raw sewage, while 250 to 435 mg/L may be adequate for secondary effluents.

Some problems with the use of lime are:

1. lack of availability and difficulty of transport;
2. pH may have to be adjusted afterwards;
3. sludge accumulation (however it may be recycled);[44] and
4. the pH must be greater than 11.0 for effective disinfection.

IEC[44] concluded that lime disinfection would cost about an order of magnitude more in annual costs than chlorination.

7.5.2.3 Iodine

The influence of temperature and pH on the bactericidal effect of iodine has been explored by Chambers *et al*[303] and the virucidal effects and temperature was studied by Berg *et al*.[304]

Iodine on a weight basis has a disinfecting power about four times that of monochloramine for *E. coli* and a much higher efficiency for reducing virus and protozoal cysts.[305] It has been found to be less influenced by pH and temperature and much more stable and easier to handle than chlorine and since lower dosages of iodine are required, lower residuals may be present.

A cost comparison with chlorine indicated iodine to be 57 percent more expensive.[306]

7.5.2.4 Ultraviolet Light

Ultraviolet disinfection of wastewater has been suggested as the most promising process currently available.[307] Advantages may include:

1. no changes in wastewater characteristics as with chemical applications and nothing is added to the effluent;
2. no danger of overdose;
3. relatively simple to operate; and
4. high bacterial inactivation within seconds.

One study[3**] found that pathogenic bacteria and viruses had equal or greater sensitivity to UV light than fecal coliforms.[3**] Gordon[3**] noted that development of an of an automated, failsafe system was feasible. Some disadvantages may be:

1. UV light is limited by its inability to penetrate turbid wastewater; and

2. a higher initial capital investment.

7.5.2.5 Ozone

Ozone was shown to be an effective disinfectant at low temperatures.[12* 3**] The time required for disinfection was short and the production of toxic residuals was minimal. Dissolved oxygen was also a decomposition product. A serious disadvantage is the gas must be generated on site since it is unstable and reduces to oxygen.

Work was done by Given and Smith[12* 12*] with ozone. They found three to four log reductions of indicator organisms at 20 to 40 mg/L ozone when raw, dilute wastewater was treated. Lagoon contents with a similar BOD required a similar ozone dose. They observed increased indicator organism reductions with decreasing temperatures. Additional benefits were reductions in COD, BOD, and increased dissolved oxygen concentrations. Some cost aspects were explored by IEC.[1**] IEC concluded that ozone was not presently cost effective.

7.6 MECHANICALLY AIDED METHODS

In some cases, it is desirable to upgrade the lagoon effluent by auxiliary aeration and rotating biological contactors (RBC) which can be much smaller and less expensive than if used in lieu of lagoons altogether.

7.6.1 Auxiliary Aeration

Several reports focussed on instances of overloaded facultative lagoons being successfully converted into mechanically aerated facultative lagoons.[310] [311] Information on the performance of aerated facultative lagoons in Alaska was found in several sources.[312] [313] [314] [315] [316] [317] [318]

Auxiliary aeration may reduce the normal retention time or allow increased loading without concomitant odour problems. Aeration also discourages stratification thereby minimizing short circuiting.[319] BOD loading on aerated lagoons was reported to be five to ten times that of a facultative lagoon.[311] Champlin[320] stated that 127 kg BOD_5/1000 m^3 was the upper limit for supplementary aeration, while Boulier and Atchison[311] indicated 48 kg BOD_5/1000 m^3 was a typical upper limit. Temperature is a major factor in determining these limits.

Tilsworth and Smith[143] commented that in the event of anticipated anaerobic conditions during the spring thaw, floating aerators could provide needed aeration on a temporary basis. Provision must be made for benthic oxygen demand from accumulated

sludge in the spring. Marais[3,4] indicated oxygen demands at this time may exceed three to five times the influent BOD_5 load.

Landine and Viraraghavan[3,21] reported on a small inexpensive floating aerator adaptable to northern climates with a submersible motor resistent to freeze up. Most northern applications have used diffused aeration since mechanical aerators have proved unreliable when operated in heavy ice conditions.[3,13] [3,22] [3,23]

The literature suggested that an oxygen supply of 0.45 to 0.68 kg O_2/kg BOD_5 should be supplied to satisfy BOD loading.

Adams and Eckenfelder[3,24] recommended a minimum aeration power input of 0.75 kw/1000 m^3 of lagoon volume. This is to ensure availability of dissolved oxygen in all parts of the lagoon. Reid[3,13] presented an example to determine the brake horsepower for an air pump.

Nitrification may occur in long retention lagoons. Therefore the additional oxygen demand from this source must be considered where this may occur.[4,7]

The Ontario Ministry of the Environment has undertaken pilot and full scale studies on aerating lagoon effluents to remove hydrogen sulphide (H_2S).[3,28] Although some difficulty was experienced in maintaining sufficient liquid depth to ensure efficient O_2 transfer, the results were felt to be satisfactory. They cited other advantages such as:

1. a shortened period of ice cover;

2. low mixing intensities which promoted gravity sedimentation;

3. no interference with existing phosphorus removal practices was evident.

In another laboratory experiment, a post aeration column was utilized.[325] Although impressive effluent H_2S removals were achieved, the odour problems originating in the preceding lagoons were not. The costs were found to be lower as compared with aerating the whole lagoon contents when H_2S removal was the criterion. Added benefits of this method were said to be increased dissolved oxygen and the oxidation of other materials in the effluent.

7.6.2 Rotating Biological Contactor

Low maintenance and stability of RBC's under fluctuating organic and hydraulic loading has been reported by Sack and Phillips.[326] Other advantages include low energy use and minimum operating skill which makes this system suitable for application as a package plant in small or remote communities where secondary quality effluent is desired.[104] They must be covered and heated as RBC's are effective heat transfer units. Given and Smith[327] reported the use of an RBC for treating dilute, cold wastewater with favourable results. The application to lagoon effluents was not considered. Rupke and Chisholm[274] found an RBC unit to be the most effective upgrading approach on a lagoon in southern

Ontario.

7.7 AQUACULTURE AND BIOLOGICAL ENHANCEMENT

Aquaculture in cold regions has been reported by Serfling and Alsten,[328] Pershe,[329] and Reed and Bouzoun.[330]

A case is made for optimizing the design of maturation ponds for *Daphnia* culture by Dinges[81] and introducing fish.[330] Daborn *et al*[82] studied the ecology of *Daphnia* in a Nova Scotia sewage pond in the winter and summer. Neil[331] investigated the feasibility of removing phosphorus, nitrogen, and organic matter through biological uptake and harvest of algae, duckweed, *Daphnia*, and midge larva in Ontario sewage lagoons.

Other options in aquaculture included fish, a variety of zooplankton, and water plants such as water hyacinths and bull rushes.[47, 332]

Romanenko[333] reported on a batch addition of selected algae to improve spring BOD removal following spring break-up. Beyond noting a four fold decrease in BOD, no other information was presented.

Deutsch[334] discussed waste treatment boosted by bacterial additions. Some claims associated with bacterial culture additions in activated sludge units, included improved start-up, more stable operation and improved BOD removal. Their use is probably limited to speeding up natural population dynamics and

species distribution. However, more research into this area may prove fruitful, especially with regards to psychrophilic bacteria.

7.8 FACILITY AND OPERATING MODIFICATIONS

7.8.1 Facility Options

For a continuous discharge facility, hydraulic short circuiting has been the most serious problem.[44, 333]

Plug flow hydraulics appear to best describe the regime of a facultative lagoon therefore upgrading efforts tend to promote conditions of plug flow.[47] Placing baffles in the lagoon was proposed by Middlebrooks *et al*[47] but icing problems have occurred in cold climates. Constructing additional cells in series, promotes PF conditions and reduces the suspended solids loading in the effluent.[333]

Inlet-outlet structures may be important causes of short circuiting. Reconstruction or retrofitting additional structures may improve this situation.[333]

7.8.2 Operating Modifications

Controlled discharge is a simple method of upgrading cold climate lagoons.[47] Pierce[334] studied the effluent quality of controlled discharge facilities in Michigan. Consistently high quality was reported for autumn discharges. Alberta

Environment[23] studied long retention lagoons (365 days) which discharged during the summer only. Values of BOD_5 and SS less than 20 mg/L were reported.

Graham and Hunsinger[18] used the batch mode of a controlled discharge facility for phosphorus removal by alum addition.

Hatcher[24] recently published a report analysing controlled discharge facilities and attempted to rationalize the problem of "when to discharge". She proposed several alternatives based on hydrographs. Current practice in Canada involves "eyeballing" the receiving water for the best time to discharge.

Pond phase isolation has been found to promote autoflocculation of algae.[7] Koopman *et al*[28] studied phase isolation.

Caldwell *et al*[29] suggested using recycle as a method of improving the performance of a continuous flow system. This is a poor cousin of activated sludge.

7.9 CRITIQUE

There are several upgrading techniques which are applicable to northern lagoons. These include rapid infiltration and wetlands land treatment, chemical coagulation, disinfection, mechanical add-ons, addition of new facilities, and operational changes. Keeping northern climate, the relative isolation of communities, and high energy costs in mind, the list of feasible

upgrading alternatives can be reduced to land application, chemical coagulation, disinfection, operating and facility changes.

Land application is limited by soil conditions (permeability, permafrost) and the thermal regime of the area. Wetlands/peatlands application has merit but research is ongoing and results are encouraging. This topic needs more detailed study.

In-situ chemical coagulation of controlled discharge lagoons can be very effective in removing BOD, COD, SS, nutrients, and microorganisms. Detailed research is planned in Alberta.

Disinfection of wastewater is a continuing controversy though the presence of persistent microorganisms in ice covered lagoons and rivers warrants concern. Ozone and UV are amongst the most effective disinfectants at cold temperatures. Though more costly than chlorine, both have less environmental impact and are not toxic to fish. The development of modular units would greatly improve water and wastewater disinfection opportunities in the north.

Mechanical add-ons may improve effluent quality but at the cost of unreliability and high maintenance costs. Where the situation warrants, as in large centres with an existing service infrastructure, aeration and RBC units can be justified, but for the typical small settlement these do not fulfill the goals of lagoon treatment introduced in Chapter 1.

If aeration is desired, then the areas which require more work for northern applications are:

1. determine if mixing or aeration requirements should take precedence;
2. establish a minimum power level for northern lagoons;
3. establish soluble BOD_5 released from the sludge layer;
4. examine power versus suspended solids levels; and
5. investigate most effective aeration equipment.

Continuous flow lagoons may not be practical for cold climate applications. Consideration should be given to designing lagoons with over winter storage capability which may then be discharged during the summer when treatment efficiency is at an optimum. Cell and phase isolation should be studied for application in cold regions and incorporated into new lagoon designs.

8. EFFLUENT DISPOSAL CONSIDERATIONS

8.1 INTRODUCTION

Wastewater treatment effluents are disposed of in a variety of different ways including land application, evaporation, groundwater recharge, and surface water dilution.[4] Surface waters are the most common form of waste disposal but the fragile northern environment demands closer attention to the impact of municipal wastes.[3,7]

8.2 SURFACE WATERS

8.2.1 Assimilating Capacity

Surface waters offer a wide range of services to man including numerous recreational activities, commercial fishing, water supply, and waste disposal. Concern for receiving waters has revolved around dissolved oxygen levels and stream assimilative capacity.[3,6] [3,7] Concerns have been expressed regarding toxic wastes, the biological quality of effluents, and the impact on public health.

Traditionally, dissolved oxygen, nutrients, and suspended solids have been of concern because of the impact on commercially viable fish.[3,6] Much effort has been put into water quality management with numerous models of increasing complexity being developed to predict the assimilative capacity of a stream and

the impact of pollution events.[338] [341] A special problem of northern interest is thermal pollution and its impact on the thermal balance of northern lakes and streams. As discussed in an earlier section, only small changes of temperature in warm permafrost can have catastrophic impacts on the environment and man-made structures.[13] [14]

The need to document water quality and gather an extensive data base has been partially satisfied by several studies.[342] [343] [344] [345] Environment Canada[346] compiled national water quality data (NAQUADAT) for parameters related to domestic wastewater pollution.

There have only a few studies on assimilative capacity of ice-covered, northern rivers.[347] [348] [349] [350]

Dilution as the solution to pollution is an old technique which is applicable only if mixing is taken into account. Mixing is of great importance in rivers receiving effluent as Smith and Gerard[351] and Putz *et al*[49] have pointed out. The Northwest Territories Water Board[46] calls for dilution based on minimum flows.

8.2.2 Dissolved Oxygen

Schallock *et al*[340] and Gordon[47] reported an appreciable oxygen demand in an ice-covered river when sufficient nutrients were present. This finding was supported by other investigators in Alberta.[347] [352]

Studies by Schallock and Lotspeich[8.1] and Muller *et al*[8.2] found that natural oxygen levels in some Alaskan rivers drop below 1.0 mg/L naturally. Associated Engineering Services[8.3] found that the Peel, Liard, and Mackenzie Rivers had about 5.0 mg/L dissolved oxygen.

Algal discharges from lagoons are known to have caused rapid oxygen depletion in receiving waters.[8.3] [8.4] [8.5]

8.2.3 Eutrophication

A second area of interest are nitrogen and phosphorus contributions to northern rivers and lakes.[8.6] Associated Engineering Services Limited[8.3] estimated that contributions to arctic streams from municipal discharges were about one percent of the background levels and would have a negligible impact. Eedy[8.6] estimated that levels of nutrients found in southern lakes would have less impact on northern lakes. Berger[8.7] recommended establishing levels for phosphorus and nitrogen at 0.15 mg/L and 1.0 mg/L, respectively, to prevent eutrophication of northern lakes.

8.2.4 Dissolved and Suspended Solids

Associated Engineering Services Limited[8.3] reported that total dissolved solids (TDS) would increase by less than one percent in the Peel, Liard, and Mackenzie Rivers. McGauhey[8.8] recommended 2000 mg TDS/L as an upper level in fish habitats. Suspended solids can impair fish spawning, therefore the NWT

Water Board[44] limits effluent SS to between 35 and 250 mg/L depending on the dilution ratio.

8.2.5 Impact on Biota

Frey *et al*[339, 340] and Gordon[47] observed ecological and dissolved oxygen conditions in the Chena River in Alaska and concluded most of the dynamic changes resulted from municipal wastewater. Few studies have been done on fish DO requirements in northern lakes and rivers.[339, 340] The U.S. EPA stated that a minimum of 6.0 mg/L DO was required for cold water fish such as trout and salmon.

Efforts to improve the biological quality of effluents by chlorination have resulted in residual chlorine levels which are toxic to indigenous aquatic fauna.[341, 342] Residuals as low as 0.1 mg/L were reported to upset the ecological balance of receiving waters.[343, 344, 345, 346] Many treatment facilities discharge wastes containing greater than 1.0 mg/L of chlorine.[347]

Ammonia toxicity has been noted by several researchers.[348, 349, 350, 370] Limits have been proposed by the U.S. EPA[371] and Yake and James[372] at 0.02 mg/L NH_3-N.

Hydrogen sulphide has been recognized as a compound toxic to aquatic fauna, requiring limits of 0.02 mg/L in Ontario.[328, 373]

8.3 LAND

Contamination of the groundwater is a major concern in the application of wastewater to the land surface. High ammonia and nitrate levels may occur in groundwater posing a potential health hazard for infants if used for water supply.[4] Most microorganisms remain in the upper metre of the soil horizon due to adsorption and filtration.[3,4]

SNC Tottrup Services Ltd.[3,4] performed a follow up study on land application of sewage two years after irrigation. The study areas included Fort Simpson, Norman Wells and Tuktoyaktuk. They concluded that sewage had a negligible effect on the native vegetation two years after application. However, land sewage disposal was not recommended as a major disposal method in permafrost areas. The threat of rapid saturation of the soil and potential contamination of the groundwater and surface water were cited as reasons.

8.4 LEGISLATION

Two acts of primary importance in the north are the federal Northern Inland Waters Act (NIWA) and territorial Public Health Ordinance (PHO). The Public Health Ordinance is largely administered by the Federal Department of National Health and Welfare, and basically establishes the planning, design and operation requirements for all water and sanitation facilities.[3,5] [3,4] NIWA is administered by the Department of

Indian Affairs and Northern Development which is primarily interested in preserving the quality of inland waters as opposed to public health. Presently, NIWA is evolving and incorporates the experiences and attitudes established elsewhere in Canada as a guide in the development of acceptable water and sanitation facilities and services in the Northwest Territories.

Other pertinent legislation includes:

1. the NWT Environmental Protection Ordinance;
2. the Fisheries Act;
3. the Arctic Water Pollution Prevention Act; and
4. the Ocean Dumping Control Act.

NIWA formed the NWT waterboard and the Yukon waterboard which developed municipal wastewater discharge guidelines.[44, 77] They are site specific guidelines and recognize the wide variability of population distributions and dilutional capacities of various surface waters.

Another set of guidelines of interest are those for federal establishments in Canada.[78] These guidelines were established to set an example of concern for environmental protection in Canada. The imposed limits require carefully designed and properly operated treatment systems.

8.5 CRITIQUE

Principal topics of interest in northern Canada deal with the assimilation capacity of northern streams and lakes. The only work done to date has looked at stream assimilative capacity for dissolved oxygen demand and microorganism survival. Recent research on the mixing regime of a northern river and the fate of a non-conservative municipal discharge has pointed the direction of water quality management in the north.

Information on the components of a northern river or lake oxygen balance is largely unknown though it is recognized that natural demands from groundwater, metal ion oxidation, and microorganisms have a large impact on northern rivers.

Thermal models of lakes and rivers are inadequate and require further research if reasonable assessments of the impact of waste discharges are to be known.

Southern water quality management techniques have not been applied to date on northern waters. The fragility of northern ecosystems requires planning, not crisis management.

9. PUBLIC HEALTH ASPECTS

9.1 INTRODUCTION

Properly designed and operated lagoons, operated in series, are capable of producing secondary quality effluent with fecal coliform levels less than 200 per 100 mL in warm climates. Once water temperatures drop below 15° to 20° C indicator organisms persist longer and less than two $\log_{10}$ unit reductions are common at near freezing temperatures. The impact of releasing large numbers of indicator organisms into the environment is largely unknown, however recent research suggests that a serious public health hazard may exist from organisms with transferable drug resistance.[3,9]

Feachem *et al*[4] compiled a state of the art review of sanitation, disease, and the sanitary effectiveness of various sewage treatment processes. They found properly designed lagoons to be the best in reducing pathogens.

9.2 WATERBORNE DISEASE

Wastewater is one of the most important sources of enteric pathogens. Causal agents comprise viruses, bacteria, protozoa, and helminths.[3,4] Common enteric diseases and their etiology are given in Table 9.1. Incidences of disease related to poor sanitation have been greatly reduced in North America and that which does occur is commonly viral gastroenteritis.[3,4,12]

Table 9.1 – Some Commonly Excreted Pathogens
(after Feachem *et al*[11])

Group	Agent	Disease
Viruses		
	Coxsackie virus	Various ailments
	Hepatitis A virus	Infectious hepatitis
	Norwalk agent	Gastroenteritis
	Poliovirus	Poliomyelitis
	Rotavirus	Gastroenteritis
Bacteria		
	Campylobacter fetus	Enteritis
	Escherichia coli	Gastroenteritis
	Leptospira spp.	Leptospirosis
	Salmonella typhi	Typhoid fever
	S. paratyphi	Paratyphoid fever
	Shigella spp.	Bacillary dysentry
	Vibrio cholerae	Cholera
	Yersinia enterocolitica	Yersiniosis
Protozoa		
	Entamoeba histolytica	Amebic dysentry
	Giardia lamblia	Giardiasis
	Naegleria fowleri	Meningoencephalitis
Helminths		
	Ascaris lumbricoides	Ascariosis
	Diphyllobothrium latum	Fish tapeworm

Hrudey and Raniga[333] summarized national health statistics which indicated that incidences of infectious hepatitis, shigellosis, and salmonellosis were significantly above the national average in Alberta and the Northwest Territories. Gastroenteritis was the most common complaint.

Bell,[334] Bell and Cole[335] studied fecal coliform die-off following spray irrigation of land in southern Alberta, finding 10 hours of direct sunlight to be effective in killing the bacteria and after a few more days the soil was felt to be no longer a public health hazard. However, as noted by Bell,[334] these findings only represented a specific test area and the probable reason for the variation in findings reported in the literature was due to differences in local flora and climate.

SNC-Tottrup[336] investigated the parasitology of land application of sewage in the arctic. They found public health risks asscoiated with *Iodamoeba butshlii*, *Diphyllobothrium latum*, and *Entamoeba coli*. Sand filtration of the sewage effluent was recommended prior to land application. These findings contrasted markedly with those of Feachem *et al*[48] who noted that *Ent. coli* and other protozoa such as *Iodamoeba* were not pathogenic and the helminth, *D. latum*, was not an important parasite since it required an intermediate host (fish) before it infected man. Provided runoff did not contribute to surface water infestation there is little direct risk involved. Feachem *et al* agreed that sand filtration probably would remove protozoa and helminth eggs.

9.3 INDICATOR ORGANISMS

The use of indicator organisms came about due to the difficulty of isolating and identifying various waterborne pathogens from the extensive flora of the human intestinal tract.

The characteristics of an ideal indicator organism are:''

1. present only in the intestinal flora of healthy people;
2. absent from non-human animals;
3. present only when pathogens are present;
4. present in larger numbers than pathogens;
5. unable to grow outside of the intestine;
6. die-off rate the same as pathogens or slightly slower;
7. resistant to waste treatment processes to a greater degree than pathogens;
8. easy to detect and enumerate; and
9. non-pathogenic.

There is no indicator which satisfies these criteria.

Geldreich[3''] summarized the flora of human feces of which a few groups were found in large numbers. These included coliforms, fecal coliforms, *Escherichia coli*, fecal streptococci, and enterococci. The coliform group is not a taxonomic classification but is one of convenience and is defined by Standard Methods for

the Examination of Water and Wastewater[1] as;
"aerobic and facultative anaerobic, gram-negative, non-spore forming, rod shaped bacteria which ferment lactose with gas formation within 48 hours at 35° C".
Olivieri[2] noted that the coliform group has some shortcomings which included:

1. die-off rates which are significantly greater than viruses and protozoa;

2. higher sensitivity to treatment processes than pathogens;

3. aftergrowth potential; and

4. the ability to compete successfully in the environment which alters the ratio between coliforms and pathogens unpredictably.

Even with these deficiencies, no other group comes closer to satisfying the criteria for indicator organisms than the coliform group.

Subdividing the total coliform (TC) group down to the fecal coliforms (FC) is useful since total coliforms include some soil bacteria which are ubiquitous whereas fecal coliforms are comprised of genera from Enterobacteriaceae and originate exclusively in the feces of warm-blooded animals. While it has not been possible to establish a meaningful TC/FC ratio, there has been some success with the fecal coliform:fecal streptococci (FS) ratio.[3] Pollution of human origin has FC/FS ratios greater

than 4 while that of non-human origin is in the range of 1 or less.[341] This has been a satisfactory delineation in raw sewage, however in the receiving environment it has been less so due to mixing and uncertain travel times.

The adequacy of *E. coli* as an indicator in cold water has been questioned by Miyamoto[162, 339] and Drapeau.[340] Drapeau concluded that *Pseudomonas aeruginosa* should replace *E. coli* at temperatures less than 4° C. Miyamoto disagreed with this and found *P. aeruginosa* to be unsuitable.

A serious shortfall of indicator bacteria has been their inability to exclusively indicate the presence of viruses.[341] Cabelli[342] produced epidemiological evidence that Rotavirus and Norwalk virus were responsible for gastroenteritis in swimmmers. He found neither total coliform nor fecal coliform were adequate indicators. In another study, Cabelli *et al*[343] found enterococci to have the best correlation with incidences of gastroenteritis in swimmers. They reported less than 10 *E. coli* per 100 mL were present.

Some researchers suggested establishment of viral indicators for the routine biological investigation of water and wastewater.[341] The use of phages – viruses which attack bacteria – has been advocated but published reports on methods of detection and sensitivity for use on a routine basis are rare.[344] A World Health Organization Scientific Group[341] felt that much more research was needed in this area.

9.4 PERSISTENCE OF MICROORGANISMS

An important characteristic of microbes is their ability to remain viable under adverse environmental conditions such as those found in treatment processes. As noted in the previous discussion, very low indicator counts were associated with viral gastroenteritis indicating longer viral pathogen survivals than bacterial indicators.

The literature reported persistence was mainly a function of temperature and time.[11 398 396 397 398 399] McGarry and Bouthillier[7] reported temperature and organic loading to be important in the survival of *Salmonella typhi* in a lagoon.

Most Canadian treatment facilities use surface waters to dispose of effluent. These waters are frozen over for 6 to 8 months of the year and have water temperatures near freezing. Smith and Gerard[351] speculated that lagoons allow microorganisms to escape thermal shock by gradually acclimatizing in the lagoon environment. Slanetz *et al*[400] carried out a study of bacterial and viral survival in a lagoon system in New Hampshire. Their temperature data were inadequate. However, higher persistence was reported during the winter months.

Gordon[401] and Davenport *et al*[402] reported indicator persistence 2.7 to 5.4 times longer in arctic rivers than previously reported for southern winter conditions. Dahling and Safferman[403] found enteric viruses had a survival rate of 34 percent over a 320 km reach of the Tanana River in Alaska. This

supported earlier findings by Prier and Riley[4.4.4] who found that Echovirus, Coxackievirus, and Poliovirus were stable in 4° C river and impoundment waters. Katzenelson[3.4.4] stated that viable viruses can be stored indefinitely at deep-freeze temperatures and expected long survival times at 0° to 5° C. Clarke *et al*[4.4.5] described results which suggested viruses may remain viable for greater than 200 days at temperatures less than 4° C. Also they found that Poliovirus survived three times longer than *E. coli* and *Streptococcus fecalis*. Bitton[4.4.6] reported virus survival of 40 to 90 days at 3° to 5° C under laboratory conditions. Yamamoto *et al*[4.4.7] reported the initial findings on the virus content of lagoon effluents in the Northwest Territories and locations in Alberta. They found substantial numbers of viruses on a routine basis at all locations. This supported the earlier reports by Slanetz *et al*[4.4.8] [4.4.9] who found viruses in the lagoon effluent on a regular basis. Berg,[4.4.9] [4.4.10] and others[4.4.8] [4.4.11] have reported similar findings in all climates. This poses a serious health hazard since the infective dose of viruses is small.

There is evidence that microbes remain viable for long periods in cold climate lagoons and that large numbers of pathogenic bacteria and viruses are being discharged into the environment.

9.5 BACTERIA AND R FACTORS

The problem of transferable R factors was first discovered by Japanese researchers in 1959 while studying the outbreak of drug resistant *Shigellae*. The phenomenon results from a group of plasmids – extrachromosomal genetic structures composed of DNA – called resistance transfer factors (R factors) which are able to travel by cell to cell contact.[4]

R factors are responsible for acquired resistance to antibiotics, toxins, heavy metals, ultraviolet light, bacteriocins, and phages. The ability of Enterobacteriaceae to transfer R factors amongst themselves has great implications for public health. Grabow *et al*[3,7] reviewed the problem in depth and noted that Enterobacteriaceae acts as a reservoir for R factors and will transfer them to pathogens. They suggested that water quality standards should be reviewed in light of R factors.

Bell *et al*[4,2, 4,3, 4,4] investigated the occurrence of R factors in the sewage flora of northern Canada and the Prairie Provinces. The remote northern Slave River had low incidences of antibiotic resistant fecal coliforms; 7.1 percent having multiple drug resistance and 0.79 percent with tranmissible drug resistance. This differed markedly from the Red River in Manitoba where Winnipeg waste discharges are a major source of drug resistant fecal coliforms; 52.9 percent having multiple drug resistance and 18.77 percent with transferable resistance. They found 10.8 percent of fecal coliforms in raw sewage had R factors as did 8.9 percent of total coliforms. The authors speculated

that 9 to 11 percent of the natural flora in the Red River have R factors and these organisms appear to compete favourably in the aquatic environment. Grabow[111] warns of lakes, rivers, and impoundments acting as reservoirs for R$^+$ organisms – those with transferable R factors.

Sewage lagoons appear to be ideal environments for R$^+$ organisms and their incidence has been investigated. Grabow[111] reported 1.8×10^4 total coliforms per 100 mL had transferable drug resistance in a lagoon in South Africa. Kish and Lampky[114] studied a long retention, seasonal discharge lagoon in Michigan and found total coliforms persisted over the winter months with numbers peaking at 10^3 per 100 mL during the spring turnover. Proportions of drug resistant organisms decreased over the winter but increased through the three pond system. No summer samples were taken. The effluent had greater than 60 percent of total coliforms with drug resistance. Bell *et al*[114] recently reported the survival incidence of R$^+$ fecal coliforms in a continuous discharge, long retention lagoon system at Fort Smith, Northwest Territories. They found the proportion of R$^+$ organisms increased over the winter. The effluent fecal coliform population contained 58 percent with resistance to three or more drugs and 4.02 percent with transferable drug resistance.

The incidence of reported R$^+$ organisms are increasing and play an increasing role in the outbreaks of drug resistant bacterial epidemics which may have a significant impact on public health.

9.6 FOOD HARVESTING

Associated Engineering Services[111] concluded that fish and other aquatic life harvested for human consumption do not in general accumulate pathogenic organisms. However, fish harvested from polluted water have been known to concentrate fecal coliforms.[88] The most likely transmission route of pathogens is either by direct human contact during the cleaning process or through consumption of undercooked flesh contaminated during cleaning.[118] Small marine effluent discharges were considered beneficial since they enhanced general habitat productivity and increased fish populations.[117] Trimberger[333] and Henderson[119] analyzed the flesh of fish grown in lagoon wastewater for pesticides, heavy metals, and common waterborne pathogens, and found levels to be well below the guidelines established by the U. S. Food and Drug Act.

9.7 RECREATION

Correlation between mean enterococci densities and incidences of swimming associated gastroenteritis have been investigated by Cabelli and others.[88] [81] The responsibility must be shouldered by the community to ensure that surface waters frequented by recreational activities are not pathogenically contaminated beyond established guidelines or regulations for contact activities.

9.8 FENCING AND SIGNS

Christensen[3,8] recognized the need for public safety concerns in the vicinity of sewage treatment facilities, including outfalls and land application locations. Fencing and/or signs should be provided on the perimeter of facilities warning of the hazard to people and health. Lagoon fencing and signing should be placed at the base of the impounding berm.

Normal buffer requirement for lagoons, and any effluent outfall, is 500 metres from the nearest inhabited dwelling as prescribed by the Northwest Territories Public Health Ordinance regulations.

9.9 CRITIQUE

The biological water quality is a parameter which undergoes a great deal of variation over the seasons as illustrated in Figure 1.1 (c). It is highly likely, that significant numbers of viruses are discharged with the lagoon effluent since they have been shown to be present in large quantities and to persist for long periods of time at cold temperatures. Pathogenic bacteria are also likely to persist for long periods of time in a cold receiving environment. The high incidences of gastroenteritis of unknown origin, likely the water route, are possibly as a result of viruses penetrating a community's water supply, particularily in the north where minimal water treatment is carried out.

A second area of biological pollution that has long term implications in public health, is the presence of R' organisms in lagoon effluents. The lagoon environment has excellent characteristics for promoting transfer of drug resistance from benign organisms to pathogenic ones.

Disinfection of lagoon effluents is the obvious solution to reducing the public health impacts, but as discussed in an earlier section, the options must be carefully assessed, and the mechanisms of disease transfer in northern communities defined. Chlorine has many disadvantages. It may cause long term detrimental effects in the environment, without effectively reducing the most serious pathogens, viruses and bacteria with R factors. Alternatives such as ozone which has proven virucidal effectiveness but lacking known toxicity or production of hazardous organic compounds, should be actively researched and developed for use with lagoons. The cost disadvantage has not been analysed on an overall treatment basis and this process should not be discounted until a more comprehensive study is done.

There is some question as to the best indicator organism to use in cold (< 4° C) water. There is very little published on this area.

Adequate retention times at 20° C plus temperatures can be the most economical method of improving the biological quality of lagoon effluents as outlined in an earlier section but this is only possible for systems with controlled discharge.

10. ECONOMIC FACTORS

10.1 INTRODUCTION

There is little relevant lagoon cost data in the literature, particularily with respect to the far north.

Torpy[223] compiled oxidation pond costs for land acquisition, construction and operation and presented the information graphically as a function of flowrate and seasonal discharge. The costs are in 1978 U.S. dollars and were gathered from the lower 48 states.

10.2 CAPITAL COSTS

10.2.1 Land Acquisition

Gloyna' summarized land costs for lagoons compared with secondary treatment plants and found costs to be about twice those of the plants.

The special case of northern Canada, where all land is Crown land may not cause a problem with land acquisition costs.

10.2.2 Construction Costs

There is virtually nothing published on construction costs in the north, however it is certain that the numerous contracts awarded each year by Environment Canada and territorial

governments can give some guidance in this area. Smith *et al*[18] provided some rough estimates.

10.3 OPERATING COSTS

10.3.1 Routine

Routine maintenance involves grass cutting, mosquito spraying, checking appurtenances and sampling. This is not usually full-time work in small communities therefore the costs can be low.[1]

The energy requirements of a lagoon system are the lowest of the secondary processes.[1]

10.3.2 Infrequent

Infrequent maintenance operations include seasonal discharge and sludge removal.

Costs for sludge removal would depend on the method employed and the availability of the appropriate equipment. No literature is available on the costs involved in a northern settlement.

Seasonal discharge could be done by one operator for several small communities as discussed in Section 7. The costs of training, salary, and transportation could be spread over several communities creating attractive operating costs.

10.4 CRITIQUE

There is nothing in the literature on the capital, operating, or monitoring costs of northern wastewater treatment facilities in general and lagoons in particular.

A need exists for a cost compilation of water and wastewater projects constructed in northern Canada.

11. SUMMARY AND RECOMMENDATIONS

As a result of this review it becomes evident there remains a number of areas which require further study. The most important topics are summarized in this section as research needs and recommendations.

11.1 PERFORMANCE

The design of cold climate lagoons has undergone significant modification in order to produce acceptable quality discharges to the environment. The decisions to reduce loading rates, increase retention time, and eventually use a seasonal discharge mode of operation, were based on visual observations and limited analytical information. The treatment performance data available are difficult to interpret due to incomplete or poorly detailed sampling procedures which prohibits meaningful comparison of influent and effluent data. For better design and operation of continuous discharge lagoons a comprehensive relationship relating seasonal influences is needed. This type of information would also provide a reliable basis for making regulatory decisions.

To date, very little has been published on the effluent quality from seasonal discharge systems. Such a study should address stochastic variation in the effluent and the effects on the receiving environment.

11.2 BIOLOGICAL PROCESSES

Cold climate lagoons have a particular problem with the accumulation of sludge. The digestion rate at low temperatures is slow and as a result of the limited digestion, sludge volume reduction is slow and the accumulation rate is higher than in southern lagoons. The optimization of lagoon sludge management through improved *in-situ* consolidation by chemical or biological means is required.

The role of psychrophilic organisms in lagoon treatment is poorly understood. Enhancing the performance of these microbes may facilitate the use of lagoons in cold weather by a simple biological modification.

Natural disinfection by predation and UV light results in effluent with good biological quality during the summer. Predictions of efficiencies and optimization of these processes may allow the development of higher quality effluents, or an extension of the time during which acceptable quality effluent is produced.

11.3 PHYSICAL-CHEMICAL PROCESSES

Improved effluent quality during the summer period can be achieved through reduction of effluent suspended solids. Research directed at biological, chemical, and auto-flocculation may yield more effective and less costly alternatives.

Chemical disinfection of lagoon effluents is required during periods, and at locations, where public health concerns exist. The inefficiencies of chlorine, high costs, difficult operation, and undesirable end products have frequently resulted in a decision against its use. Alternative methods for disinfection should be available and research into the use of these options at small communities should continue.

The complex and dynamic nature of lagoons has precluded the development of usable and reliable mathematical models. Development of a more complete stochastic model using a climate, biology, mixing, and waste descriptor would assist in understanding the process. The numerical models developed to date have been complex and have produced poor results. Components of such a descriptor may be suitable for use in identifying and resolving design and operational problems.

The effect of pH, particularily extreme values, on lagoon performance should be examined in light of the low alkalinity values found in northern waters.

The potential of adverse biological effects due to high dissolved solids concentrations requires further study. Lagoons located in coastal and low water use communities plus locations where significant ice growth occurs may be impacted by this condition.

11.4 DESIGN

In cold climates, retention time has become the design parameter. This usually involves long holding periods with one or two discharges per year. However, many existing units operate on a continuous flow basis. Evidence suggests that continuous flow and frequently discharged systems operate best in a plug flow hydraulic regime. For existing continuous flow systems, development of a baffling system to ensure plug flow yet resist ice forces is required.

Multiple cells have been used to approach plug flow conditions. The number of cells in series have ranged from two to seven or more. The number of cells, configuration, relative retention time, and the design of inlet-outlet structures are parameters which must be selected by the designer. Current literature does not delineate the optimum values for these parameters.

11.5 FACILITY CONSTRUCTION

Geotechnical understanding of frozen soils has increased greatly over the last two decades. Much of the information results in general rules of thumb and guidelines for the application of frozen soils as foundation materials. It is known that thawing will occur under a lagoon unless very expensive measures are taken to preserve the thermal integrity of soil. At this stage it is more economical to seek other wastewater

treatment alternatives or sites.

There is a lack of information on lagoon embankment design and the resulting performance in a cold region. The types of foundation soils and their state, the types of embankment material, its placement, compaction, and seepage allowances need detailed investigation. A field study of *in-situ* liners and appurtenance performance is also needed.

The nature of drainage control features for local runoff and seepage need to be examined. The problems associated with creation of a warm thermal window in an otherwise frozen soil can present major problems with impermeable membranes. Designs related to the use of controlled uplift pressure relief valves in the base of the lagoon through the liner and decisions as to where they should discharge cannot be made with current knowledge.

In some areas, designed icings may be a viable alternative for continuous discharge lagoons. Their design and use needs to be investigated.

11.6 OPERATION AND MAINTENANCE

The operational difficulties with lagoons are limited to selection of proper discharge times and the addition of chemicals for coagulation and disinfection. The proper discharge time will be somewhat site specific, relating effluent quality, downstream uses, and stream flow at the time of discharge. A guideline

covering these points should be developed. The decision of whether or not to coagulate the lagoon contents should be included.

Lagoon cleaning and the disposal of the resulting sludge is a maintenance problem which recurs on a five to ten year cycle. This may prove to be a difficult problem for lagoons with a synthetic membrane liner. Research is needed on this problem.

Odour control may be one of the most difficult problems to manage. A considerable amount of research is required to improve understanding and control of lagoon odours.

11.7 PUBLIC HEALTH

The major public health concern with respect to lagoons in a cold climate, is the fate of indicator and pathogenic organisms. Are they indeed being acclimatized in lagoons? What is the relationship between indicator and pathogen concentrations in cold water? Does the treatment system promote transferable drug resistance? And what happens to viruses, endospore-forming, and cyst-forming organisms in lagoons?

All of the above questions need to be answered by means of well designed studies. The answers will allow more rational decisions on the design and operation of lagoons and provide some insight into potentially serious public health problems.

11.8 EFFLUENT DISPOSAL OPTIONS

Discharge of lagoon effluents in thaw unstable soil regions may cause significant changes to the thermal and biological characteristics of the receiving environment. Erosion of protective vegetation and soil layers contribute to increased thawing in turn leading to an expansion of the surface area which has melted water. A method of predicting and preventing this situation is needed.

Bank discharges from continuous flow systems produce a plume of microorganisms at the one part of the river where the public is most likely to contact, therefore, a potential public health hazard exists. Outfall location and design criteria needs to be reviewed in light of this.

Current thermal models for small lakes in permafrost conditions are inadequate for predicting the effects of the effluent.

The use of swampland or wetland as disposal option or upgrading technique has been tried and appears to be successful. Further research on this approach should yield valuable design information.

11.9 UPGRADING ALTERNATIVES

Lagoon upgrading can be implemented by performance improvement or add-on tertiary steps. Performance improvement was

covered earlier. Effluent polishing can be achieved by positive effluent control (seasonal discharge), effluent filtration, and disinfection. Controlled discharge has been adopted as the most economical approach by many new facilities. However, existing lagoons or new lagoons at a site where space is limited, may require upgrading using both alternatives. Both of these need considerably more study in cold climates at pilot plant and full scale.

The conversion of existing lagoons to partially mixed units to relieve overloaded or odiferous conditions, needs further study.

11.10 COSTS

Although cost information exists in government and consultants' files, little has been published. A compilation of lagoon capital, operating, and monitoring costs should be undertaken and published.

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